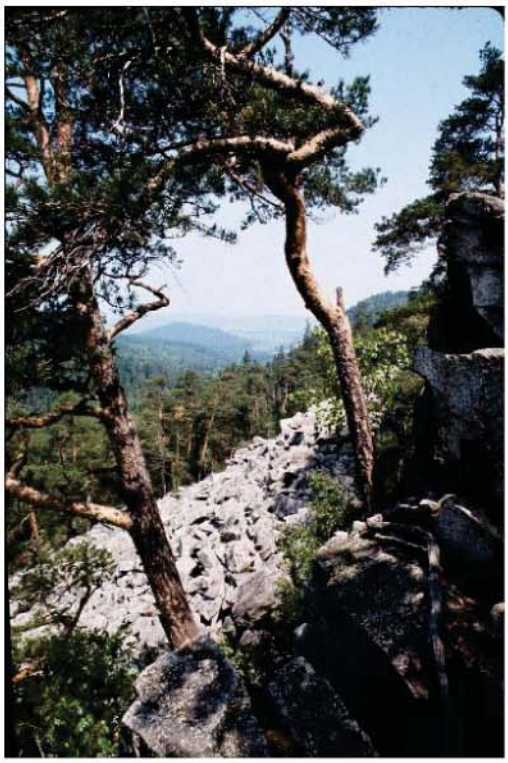

International Conference on

GROUNDWATER IN FRACTURED ROCKS

15.-19.9.2003 - Prague
Czech Republic

PROCEEDINGS

Edited by
Jiří Krásný, Zbyněk Hrkal, Jiří Bruthans

Conference jointly convened by

- *IAH Commision on Hardrock Hydrogeology*
- *IAH Czech National Committee*
- *Charles University Prague*
- *Czech Association of Hydrogeologists*

Sponsored by UNESCO

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of the International Conference on

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Extended Abstracts

15 – 19 September 2003
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FRONT COVER ILLUSTRATIONS:

Devil's Wall, South Bohemia, area of the Pre-Conference Excursion - above left,
Karlovy Vary Spa, West Bohemia, visited during the Post-Conference Excursion - below right (Photo: *Jiří Krásný)*

Devil's Wall:

Debris of granite boulders and rock-blocks on the slope of the Vltava River Valley

The site is located at the boundary between the peneplane of the Šumava Mts. and the deeply eroded Šumava piedmont-region. The peneplane is a product of a long-term base-levelling that had occurred after the Variscan orogeny. Tectonic rejuvenation of the Bohemian Massif started during Cenozoic due to Alpine-Carpathian orogenic activities having occurred in the southern and south-eastern close vicinity of the Bohemian Massif. Consequently, general uplift of the Bohemian Massif as a whole and of its particular tectonic blocks, represented by the present-day mountain regions as the Šumava Mts., has started. This uplift was accompanied by intensive erosion.
Devil's Wall occurs in an area reached by the Quaternary retrogressive erosion of the Vltava River and where river rapids have arisen. Prevailing mechanical weathering during ice ages resulted in rock-block fields, frost cliffs and other landscape features typical for a periglacial environment.
Recharge possibilities in these areas are enormous but groundwater throughflows very rapidly through such weathered zones.

Karlovy Vary Spa:

The main thermal spring in the Karlovy Vary Spa, temperature 73^0 C.

West Bohemia is very rich in mineral and thermal waters. This area acquired a world-wide reputation thanks to the spas among which Karlovy Vary, Mariánské Lázně and Františkovy Lázně are the most famous forming so-called "West-Bohemian Spa triangle". Great amount of mineral water occurrences is dispersed in their wide environs and in the neighbouring German territory as well (in Bavaria and Saxonia). Chemical type of these mineral waters, characteristic of prevailing and usually high content of sodium, sulphates, chlorides and bicarbonates and usually containing carbon dioxide, is known as so called „**Karlovy Vary (Carlsbad) type of mineral waters**". Origin of this very specific type of mineral water is presently explained by synsedimentary accumulation and/or postsedimentary gradual long-term descendant percolation of fossil solutions from different surface water bodies containing brines. Such saline surface-water bodies had occurred during different previous geologic periods of the peneplane development of the Bohemian Massif, esp. in Permian-Triassic and in Tertiary, under arid or semi-arid climatic conditions. After the tectonic rejuvenation of the Bohemian Massif in Cenozoic mineral waters have been enriched with ascending CO_2 of a postvolcanic origin. This CO_2 flux has also intensified interactions within the rock-water-CO_2 systems.

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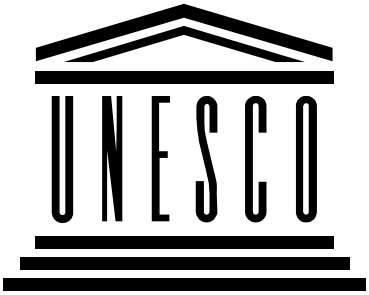

PREFACE

Fractured igneous, metamorphic and well consolidated sedimentary rocks ("hard rocks") occur in many regions all over the world. They often occur in large areas - shields and massifs and in cores of major mountain ranges. Their outcrops cover **more than 20 per cent of the present land surface**, i.e. approximately 30 million sq. kilometres. During past decades no adequate attention had been paid to groundwater in this hydrogeologic environment, except for some arid and semi-arid regions, where, under typical non-availability of surface water bodies, groundwater has traditionally represented the only source for water supply. Water demand has often stimulated intensive hydrogeologic investigations there.

During the last decade, however, **increasing interest in hardrock hydrogeology** has been noted because of many **present-day issues** that substantiate the practical importance of groundwater in hard rocks, even in temperate climatic zones:

- **Natural groundwater resources** of hardrock regions, mainly those originating in mountains, have been proved high enough to maintain flow of water courses in adjacent piedmont zones during dry periods. Natural groundwater resources (=natural recharge) sometimes with induced and/or artificial resources represent the upper limit for groundwater abstraction and sustainable water management.
- As to **groundwater abstraction**, under recent general trends of water demand increase, adequately sited water wells or other water intake systems in hardrock areas typically can cover requirements on water supply for small communities, plants or farms and for domestic water consumption. In some areas, groundwater abstraction possibilities are high enough to supply even small towns. Siting of water wells in open fracture systems or thick permeable overburden and depth-related changes in rock permeability, enabling to assess economically adequate depth of wells, are some of the important issues.
- Many-sided problems are connected with **groundwater pollution and environmental protection**. Impacts of industrialisation and urbanisation, superficial landfills and deep hazardous waste repositories, of fertilisers and pesticides used in agriculture on soil, rock and water must be monitored and reduced in hardrock environment, too. Character of groundwater flow and contaminant transport are decisive for siting of waste repositories.
- Clear hydrogeologic understanding and quantitative hydrogeologic assessments are required during various types of **geotechnical and engineering-geological activities** as construction of tunnels, underground cavities, etc., and in mining. On the other hand, these data represent an important and useful **feedback** to results provided by other hydrogeologic methodologies and techniques.
- Results of recently drilled deep boreholes in crystalline rocks re-opened the issue of **deep-seated groundwater flow and brine occurrences** and discussion on mineral and thermal water origin that are often connected with hard rocks.
- Increasing amount of available data have stimulated efforts to **regionalise and generalise results from different hydrogeologic environments**. Knowledge of hierarchy of inhomogeneity elements and of a scale effect influencing spatial distribution of hydraulic properties enables simplify real conditions when defining conceptual and numerical models of groundwater flow and solute transport.
- Data on rock transmissivity, groundwater resources and quality, obtained by different methodological approaches, offer excellent possibilities of **correlative hydrogeologic studies**. Thus new important results and conclusions can be drawn in order to understand better hydrogeologic properties of rocks both in local and regional scales.

In terms of hydrogeology, **hard rocks represent a heterogeneous and anisotropic, generally very complex environment** with irregular distribution of pathways of groundwater flow, typically consisting of three vertical zones, upper weathered, middle fractured and lower massive. Hydrogeologic knowledge and understanding of this intricate environment, based on sound geologic, hydrogeologic, hydrologic, hydrochemical, geophysical etc. studies and interdisciplinary interpretation of all results are indispensable for providing an adequate basis

for theoretical considerations, development of methodological and technical tools and applied issues to be solved. Also administrative and legislative approaches should be based on general understanding and knowledge of hardrock hydrogeology and adequate professional terminology.

Many international meetings have reflected increasing attention paid to groundwater in hard rocks. It was mainly the 24th Congress of the International Association of Hydrogeologists held in **1993 in Oslo**, focused directly on the topic of "Hydrogeology of hard rocks". Being aware of the importance of this specific environment, IAH established the **Commission on Hardrock Hydrogeology** that stimulates international co-operation and facilitate exchange of information between hydrogeologists and other specialists concerning groundwater issues in hard rocks (Commission web site: www.natur.cuni.cz/iah or www.iah.org/). Regional Working Groups of the Commission organised seven Workshops in Europe between 1993-2002. The last IAH Congresses in Cape Town (2000), in Munich (2001) and in Mar del Plata (2002) contributed significantly to hardrock hydrogeology, too.

After all these activities the Conveners of the Conference on “Groundwater in Fractured Rocks” consider useful to **sum up the results achieved in the last years and to discuss methodologies and techniques to be used in the future**. As sustainable groundwater development, protection and management in fractured hydrogeologic environments belong to the most important tasks of the present-day hydrogeology, improvement of methodological approaches, better understanding of hydrogeologic properties both on local and regional scales and knowledge of quantitative and qualitative aspects of groundwater flow would represent decisive steps to meet this aim.

Fractured or karstified carbonate and some of volcanic rocks, as well as indurated deposits of hydrogeologic basins can often be characterised by similar hydrogeologic properties as “hard rocks”. Hydrogeologic limits between all these rocks are mostly not exactly definable and applied approaches and obtained experience in one rock type might well be transferred to another. Therefore we decided not to restrict the scope of the conference only to hard rocks but to extend it to **all the fractured rocks**.

This Volume comprises more than 200 extended abstracts selected from 286 submitted abstracts of authors from 52 countries. All these extended abstracts are published in these Conference **Proceedings** and on the **CD** (on CD also optional full papers) without any difference whether they were acepted as oral or poster presentations. All the presentations are grouped into **six topics** that form, after the **keynote lectures**, the main chapters of Proceedings:

1. Hydrogeologic environment of fractured rocks
2. Groundwater flow and resources in fractured rocks
3. Chemical, physical and isotope properties of groundwater
4. Iinvestigation and interpretation methods
5. Anthropogenic impacts
6. Numerical modelling

We would like to thank the members of the Scientific Advisory Committee and our colleagues from the Local Organising Committee who willingly gave their experience, time and energy to prepare the Conference. Our thanks go also to our sponsors who supported the Conference.

We believe that the Conference will offer good opportunity to comply with all our expectations and will provide an effective professional forum for presentations and discussions of versatile issues of the present-day fractured-rock hydrogeology.

Have a fruitful and enjoyable stay in Prague and in the Czech Republic.

Prague, September 2003

Jiří Krásný and Zbyněk Hrkal

Co-chairmen of the Organising Committee

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KEYNOTE LECTURES

Groundwater exploitation in fractured rocks in South America

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A b s t r a c t : South America has a generous natural supply of water although it also has a notorious heterogeneous spatial distribution. Groundwater plays an important role and its occurrence takes place mostly in sedimentary basins occupying 70% of the territory and in areas of igneous and metamorphic rocks that include mechanically fissured water bearing units of low permeability. Interesting study cases of intensive exploitation in fractured aquifers are presented in this paper, with examples of the semiarid northeast of Brazil, in the large metropolis of Sao Paulo (Brazil), in the basin of the Bogota river (Colombia), and in the city of Cuzco (Peru). The knowledge of the hydrodynamic and hydrochemical aspects of the fractured aquifers in South America is insufficient, so it is necessary to improve the study of their potentiality inasmuch as, in all cases, groundwater extracted from these aquifers constitutes an essential support for the development of economic – productive activities.

INTRODUCTION

South America has a population of 345 million people and an area of 17.8 million km^2. Relying on a privileged natural supply of water, with a mean precipitation of 1,600 mm/year ; it reveals however a notorious heterogeneity regarding its distribution, that ranges from a few mm/year in Peru and northern Chile, to more than 8,000 mm/year in southern Chile and northeastern Colombia.

The region has large hydrographic basins with elevated rain modules, such as the Amazonas and the Paraná, large wetlands and groundwater resources of different extensions, from which the most important is the Guarani Aquifer System, shared among Argentina, Brazil, Paraguay and Uruguay, covering 1.2 million km^2.

Sedimentary basins occupy 70% of the territory, with aquifers located in porous media of variable permeability; and in areas of igneous and metamorphic rocks that include mechanically fissured aquifers of low permeability.

The proposal of this paper is to identify the main areas where fissured aquifers are located and to present some study cases of intensive exploitation of fractured aquifers in South America.

FRACTURED AQUIFER OCCURRENCE AND USE IN SOUTH AMERICA

The hydrogeological map of South America prepared by UNESCO-IHP (1996), allows the identification of areas where fissured aquifers predominate (Fig.1).

A large portion of the continent correspond to outcrops of crystalline rocks consisting mainly of granites and gneissic or migmatitic suites, sometimes covered by relatively thin and narrow Cenozoic sediments (alluvial deposits, coastal sediments and residual or transported soils).

These crystalline aquifers are in the north (Northern Shield), eastern Colombia, southern Venezuela, northern Brazil, French Guyana, Suriname and Guyana; in the centre (Central Shield), centre of Brazil and eastern Bolivia, whose small available reservoirs of interest only at a local scale.

In the semiarid northeast and humid southeast regions of Brazil (Oriental Shield), a crystalline aquifer extends across 1,500,000 km^2. Aquifer zones are associated to fractures and alignments, exploitation levels ranging from 50 to 150 m depth, and specific capacity ranging from 0.001 to 7 m^3/h m (Celligoi and Duarte 1996).

The Guarani Aquifer System in the Parana Basin, presents in its sequence a basaltic aquifer of low permeability and waters of low salinity; though sometimes with high iron, fluorine and silica content. Exploitation levels range between 100 a 150 m and specific capacity varies between 0.01 to 10 m^3/h m.

In the Argentine Patagonia, at the south of the country, in some sectors aquifers of low permeability are exploited.

Some study cases of intensive exploitation in fractured aquifers are here presented, from drilling data in the semiarid northeast of Brazil, in the large metropolis of Sao Paulo (Brazil), in the basin of the Bogota river (Colombia), and in the city of Cuzco (Peru), where the exploitation takes place by filtrating galleries.

Figure 1. Hydrogeological map of South America (adapted from UNESCO-IHP 1996)

Northeastern Brazil

Northeastern Brazil has an area of 1.6 million km^2, corresponding to 18.3% of the national territory and a population of 44.8 million people (28.5% of the country population). In this region, the climate is semiarid in 70% of the area. Regarding its groundwater resources, most of the area is dominated by a fissured aquifer of very low permeability in crystalline rocks. Well yields are low, with a mean depth of 50 m, and discharges of about 1.5 m^3/h. Another serious problem in this aquifer is salinization, reaching values of 5,000 mg/L, due to the intense evaporation and low rainfall. The total number of drilled wells in this aquifer is nearly 50,000, though 30% of them are deactivated due to low production and poor water quality.

Water consumptive use meets irrigation demands (59%), human consumption (22%), industrial and agricultural-industrial consumption (13%) and animal consumption (6%). Groundwater participation in this demand is complementary in some areas, although in others, mainly in small cities, is an almost exclusive source. In many areas of the Brazilian northeastern region, intensive use of groundwater enhances risk of resources depletion, salinization and soil subsidence. (Costa 2001).

Metropolitan area of São Paulo (Brazil)

The metropolitan area of São Paulo (Brazil) has 17.5 million inhabitants on a territory of 5,680 km^2. Groundwater resources play a central role in the complementary supply of the private sector and constitute 11% of total consumption.

The hydrographic basin of Alto Tietê, on which the metropolitan region rests, encompasses the Crystalline Aquifer System made up of granitic as well as metamorphic rocks, with a variable permeability depending on the alterations of the rock (specific discharge 0.2-1.35 m^3/h m), and the Sedimentary Aquifer System, ranging from free to semiconfined in character, (specific discharge 0.5-0.9 m^3/h m), which, in spite of occupying only 25% of the basin, is the most exploited one.

It is estimated that a large number of industries, residential areas and others use aquifer resources through 7,000 wells in operation. There seems to be an increase at a rate of 450 perforations per year due to the high fees on water service, which leads in some cases to amortise a 200 m perforation in only 6 months. Nowadays, there is interference between wells and a notorious decrease in the piezometric levels leading to a 50% reduction in the aquifer thickness. This has led to a rise in water availability costs, due to the greater electric energy consumption, perforation deepening and changes of pumping systems (Hirata *et al.* 2002).

Upper basin of the Bogota River, Colombia

It is an intra mountain range basin of 4,300 km^2, with a population of 848,000 inhabitants; aside from from the 6,500,000 inhabitants living in the capital city of Colombia, Bogota

The main aquifer is composed of Neogene-Quaternary fluvial-lacustrine sediments. It is underlain by the Guadalupe Aquifer, of secondary importance; and made up of consolidated sandstone and siltite, locally fractured and of Cretaceous age.

Guadalupe aquifer flow occurs mainly through fractures, and the transmissivity ranges from 5 to 536 m^2/day. Storage coefficients range from $1{,}10^{-2}$ to $9{,}10^{-7}$; though the most frequent values are in the range of $1{,}10^{-4}$-$1{,}10^{-5}$. In the south-western and central area of the basin, piezometric drawdown of as much as 20 m have been observed in these last 20 years; as well as an extension of the pumping cones towards the piedmont.

The waters of the Guadalupe Aquifer are calcium-bicarbonate at the piedmont and sodium-bicarbonate in the area overlain by Quaternary sediments.

The aquifer exploitation counts on 5,258 wells yielding 39.4 hm^3/year, of which 10.9 hm^3/year come from the Guadalupe Aquifer. Recharge is of 29.1 hm^3/year, defining thereby a positive balance of 18.1 hm^3/year. In the Quaternary Aquifer a balance estimated at –1. 1 hm^3/year is maintained, indicating that it is going into intense exploitation (Castrillón Muñoz and Aravena 2002).

Cusco Valley, Peru

The city of Cusco is located in the inter-mountain valleys of the oriental Cordillera of the Peruvian Andes, at 3,400 m.a.s.l. The main sources of supply are 2 lagoons yielding 350 L/s, currently overexploited; they are reporting a water drawdown of as much as 5 m from their original level. The area is characterised by a rocky outcrop covering 90% of the total surface, where fissured aquifers of the Upper Cretaceous and Tertiary lie; and 10% shows fine recent deposits, of lacustrine-alluvial origin.

The main fissured aquifer is 6,000 m thick, with transmissivity ranging from 500 to several thousands m^2/day, the real velocity ranges from 100 to 800 m/year and the fracture density is in the order of 10 fr/m^3. Waters are of the calcium-bicarbonate type, great hardness, low pH and acceptable potability.

Fissured aquifers are the most important regarding urban and agricultural exploitation, using horizontal and slanted filtrating galleries whose length ranges from 150 to 300 m, and the flow rates varies from 20 to 65 L/s, allowing gravity supply, and minimising costs of maintenance and exploitation (Apaza *et al*. 1998).

FINAL COMMENTS

Fractured aquifers in South America have a considerable groundwater potential, sometimes representing the only source of potable water available. Nevertheless, exploitation undertaken without proper management and exploration techniques lead to a high number of unsuccessful wells.

Groundwater from fractured rocks presents generally good quality, with low mineralization. Important exceptions are the crystalline rocks in the northeastern arid region of Brazil, frequently with high TDS, and some waters from basalt lava flows in the western part of that country, which eventually have high fluoride contents, leading to fluorosis in some areas.

The knowledge of the hydrodynamic and hydrochemical aspects of the fractured aquifers in South America is insufficient, so it is necessary to improve the study of their potentials inasmuch as groundwater coming from these aquifers constitutes an essential support for the development of economic – productive activities.

REFERENCES

Apaza D, Subias C, Mathieu H (1998) Explotación de acuíferos fisurados del Valle Cusco, mediante galerías filtrantes, para abastecimiento poblacional. In: Proc 4° Congreso Latinoamericano de Hidrología Subterránea, Montevideo, Uruguay (2):621-637

Castrillón Muñoz F, Aravena R (2002) Algunas evidencias de explotación intensiva de los acuíferos en la Cuenca Alta del Río Bogotá, Colombia. Boletín Geológico y Minero 113(3):283-301

Celligoi A, Duarte U (1996) Critérios hidrogeológicos na locação de poços tubulares em rochas basálticas da formação Serra Geral. Annals 2º Cong Bras Águas Subterrâneas - ABAS Salvador, Brazil (in portuguese)

Costa WD (2001) Agua subterranea no Brasil: um enfoque na regiao semi-arida. Taller Aguas Subterráneas y Gestión Integrada de Recursos Hídricos. Global Water Partnership - INA. Mendoza. Argentina. 31 pp

Hirata R, Ferrari LC, Ferrari LMR, Pede M (2002) La explotación de las aguas subterráneas en la cuenca hidrográfica del Alto Tiete (Sao Paulo, Brasil): crónica de una crisis anunciada. Boletín Geológico y Minero 113(3):273-282

UNESCO – PHI (1996) Mapa Hidrogeológico de América del Sur. CPRM

Hydrogeological similarities and differences between volcanic and hard rocks

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Volcanic rocks is a class comprising a very large variety of rocks with a wide range of chemical composition and mode of emplacement. They have in common their magmatic origin and the fact that they have been placed on the Earth surface as molten or semi-molten material, subaerially or under water, mostly at the sea bottom. Most of the volcanic rocks mass are lavas, eg. molten matter flowing on the land surface, but also as hot ash-flows fluidised by high temperature gases (ignimbrites) as rock fragments thrown into the air -pyroclasts and ash fall- or into the water -hyaloclastites-. But the piling up of volcanic matter also include intrusive bodies of molten or partially-molten materials that have not flowed to the surface and after cooling form dykes and intrusions, debris from the volcanic edifices destruction, such as laharic formations, occasional interbedded sediments, and palaeosoils.

Depending on the type of volcanism and distance to the active areas the proportion of the different constituents vary, from the dominance of pyroclasts near explosive volcanoes to the piling of only lavas away form the emission centres.

Volcanic events are discontinuous, separated by weeks or thousands of years, and may vary from the pouring of a fraction of hm^3 to many km^3. Materials can remain around the volcano or spread over many km or even some hundred km. This means that units corresponding to an event have a limited surface area, of a fraction to many km^2, and a variable thickness from some tens of metres where they pool, down to less than one metre for flows, or only mm for distant ash-fall deposits. Also these units may include many different rock types, such as hard lavas with scoria and breccia, and tuffa, be crossed by dykes, or intruded by igneous bodies, and present backed paleosoils and sediments on the top and at the bottom.

As a result hydrogeologic properties are highly variable in detail. There is a primary porosity and permeability that may be some of the largest known values or be very small, especially the permeability. These properties are associated to voids due to gas bubbles or the cracking produced by the flow of half-indurated lavas, and to shrink and flow fissures in the cooling hot mass. They form a complex anisotropic, three-dimensional network of storage and permeable features, whose homogeneous representative volume size inside a given formation may be of tens to a few hundred metres.

This primary hydrogeologic properties are not found in classical hard-rocks except for the weathered zone. This zone, which is a fraction of a metre to a few decametres thick, is paralleled in volcanic formations by a porose and permeable thickness that in some cases may exceed one km.

Volcanic rock minerals are unstable in the Earth surface and consequently they are easily weathered by water. This weathering has many aspects. Near the volcanic centre hot water may deeply weather the volcanic rocks into a very low permeability mass, and coat and fill fissures and voids with neogenic minerals.

Also cool water may alter the fine grounded vitreous ash, pyroclasts and breccias into a low permeability mass, but the hard, compact parts may remain fresh.

These processes are also different from classical hard-rocks, even from metamorphic ones, since they respond to dominantly regional effects.

Volcanic rocks are prone to secondary fissuring due to regional stress unloading and faulting, as do classical hard-rocks, but they are also fractured by compaction when new volcanic material is piled on. This is an irregular process which is poorly known, but that probably reduces macroscopic vertical anisotropy and may affect a significant formation thickness.

It can be said that thick volcanic formations approach hard-rocks with a more or less permeable and porous matrix, but without a well-defined sets of fissures, sometimes with a decreased vertical permeability, and an important drainage effect of faults and dyke-associated fissures. In low permeabity volcanics, regional values may be small while at local scale relatively high well yields may be found.

Hydrogeology of hard rocks in some eastern and western African countries

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A b s t r a c t : This article outlines the drilling results and the hydrogeological conditions of some eastern and western African countries with special focus on Liberia, Uganda, Somalia, Cameroon, with high, moderate, scarce and negligible rainfall, respectively. It gives also an overall view on the importance of rainfall and morphology in the search for groundwater in hard rocks

INTRODUCTION

Hard rock outcrops are widely extended in the various parts of the world, and cover about 20% of the land surface. Until a few tens of years ago, not much importance had been given to develop ground water from hard rock due to belief that its water potential was nil or negligible.

The rapid increase of the world population, especially in Africa and Asia, coupled with periodic droughts affecting extensive sub-desert areas of Africa, and the introduction of more efficient and cheaper drilling technology, boosted the well drilling programs in many countries. The United Nations have greatly contributed with numerous groundwater projects in more that 10 African countries, to acquire a better knowledge of the groundwater potential in many areas especially those characterised by water scarcity.

Most of the results of groundwater exploration projects have proven that hard rocks neither receive nor transmit water, unless they are fractured or weathered. The concept of aquifer is therefore related to the structural aspects of the hard rocks more than to their proprieties as groundwater conductors. The tectonic factors are, therefore, of much importance as indicators of potential groundwater body in hard rock. The fractures, often highly developed along the fault lines, and the effect of meteoric action, determine the hydraulic characteristics of these rocks being the primary porosity nearly nil. Therefore, the possibility that the igneous and metamorphic rocks act as aquifers is in connection with the existence of fracture lines that intersect each other and with highly weathered granite rocks which act as a porous media.

A statistic evaluation of the type of fractures and of their origin may help to identify possible ground water occurrence. Any type of system of fractures and fissures often tends to decrease and ends up sealing off completely. There are, however, cases of deep fissures, especially those connected with regional faults, along which the groundwater movements may occur. The movement of groundwater along shear zones and deep faults can be turbulent in various types of rocks. Their underground flow is fed by a number of small fractures and fissures having a laminar flow while the rock surrounding the fault zone may result dry or yield little water.

Groundwater investigation in Africa has proven that there are three potential water bearing zones in hard rock:

1) the upper sandy-clay zone with residual blocks of rock;
2) the zone of weathered and fractured rock, and
3) the zone of fresh, rarely fractured rock.

The upper zone is generally dry, but it may be water-bearing wherever the water table is close to the surface; the middle zone may be divided in upper deeply weathered and lower fissured, which is, in most cases, the major water bearing part of the crystalline rock, tapped by the rural village of many African countries. Groundwater in the lowest zone occurs only in deep, occasional fissures.

The main water-bearing zone is characterised, in most cases, by the irregular distribution of the water level in wells and the rapid change in chemical composition in neighbouring wells.

Rainfall, with its three factors: regime, intensity and values of evapo-transpiration, and the geomorphology, influencing the run-off and infiltration, play a very important role in the availability of ground water in hard rocks.

HYDROGEOLOGICAL ASPECTS AND DRILLING RESULTS IN SOME AFRICAN COUNTRIES

The groundwater conditions and the drilling results of four African countries, Liberia, Uganda, Somalia and Mauritania, with high, moderate, scarce and negligible rainfall, respectively, are briefly described below.

Liberia

In Liberia, West Africa, where rainfall ranges between 1700 mm/year along the border with Guinea to 4400 mm/year along the coast, geomorphology is less important. Shallow hand dug wells, even if located in watershed areas, can supply small amount of water, so far as they have penetrated thick lateritic or weathered rock cover. Experience, however, has shown that in spite of the high rainfall, only 117, out of 231 boreholes (50.65%), drilled in the late seventies for rural villages water supply were successfully equipped with pumps, 50 were dry, 21 had caving-in problems, and 8 had other problems. The successful boreholes, with depth ranging from 10 to 31 m, were located mainly in low-lying areas where water was met in lateritic material and in weathered and fractured rock. Boreholes with depth less than 15 m found little water, 75% of boreholes with average depth of 30 m, of which 15 m. penetrated the bedrock, had substantial yield; 25% of the boreholes yielded little water (Faillace 1979). The four test drilling for Zuedru Water Supply, with depths from 15 to 20 m. had a yield ranging from 0.1 to1.5 L/s.

Deeper boreholes drilled for the water supply of six towns gave better results. In fact, in 50-60 boreholes that penetrated deep in gneiss, schists and other metamorphic rocks that cover that country, groundwater conditions were rather good compared to other African countries. In particular, 16 boreholes with an average depth of 105 m drilled in Buchanan for domestic and industrial purposes had an average yield of 5000 L/h. Six additional exploratory boreholes drilled for same town had an average yield of 7400 L/h. Borehole n. 6, was pump tested when its depth was 102 m obtaining 9500 L/h; it was subsequently deepened to 151 m and it was obtained a yield of 18.200 L/h. Groundwater conditions, however, vary from place to place, and even within short distances.

The average specific capacity of wells in Bhuchanan was 0.423 m^3/h/m with a range between 0.017 and 2.240m^3/h/m (GKW 1980). No one of the deep boreholes was reported dry. The best results were obtained in coarse grained layered crystalline rocks where ground water can be found in more permeable layers acting as aquifers. The relation of groundwater to structure and topography is quite important because such features are often indicating the permeable part of the crystalline rocks. The stream courses, in fact, may be active recharge and discharge zones, often marking fault and sheer zones along which groundwater movement occurs.

Water quality is characterised by a low salt content, however, high iron content and low pH are the main water problems in Liberia.

Uganda

Karamoja region in Uganda, covers an area of 30,000 km^2 with igneous and metamorphic rocks; its average yearly rainfall is 800 mm, ranging from 500 to 1140 mm/year. In the late sixties the UN groundwater project drilled 92 exploratory boreholes. The best results of the 71 successful boreholes (78.2%) were obtained in the bottom of small valleys, where storage was combined with good permeability and good recharge. The water entries in almost all the successful boreholes where above 100 m, with exception of one case with water entry below 100 m. Water from deep water entries is often under sub-artesian conditions. Water inflows from non-interconnected fissures are often marked by abrupt change of the water level while drilling (Faillace 1973).

The best average yield and specific capacities were obtained between 45 and 78 m, however, considering the overall results, the optimum depth of the wells in the metamorphic rocks of Karamoja lies between 30 and 90 m.

The boreholes were located in five different geomorphologic positions: flat valley, riverside, flat pediment, pediment, watershed, with an average yield of 3008, 1661, 857, 525, and 366 L/h respectively. In most cases, the good results were due to deep weathering of the basement rock overlaid by alluvial cover. The yield of wells was very variable, large difference in yield occurred in boreholes located at only a few metres apart, although being drilled in similar conditions. This shows that the type of weathering and structural features, rather than to rock lithology, determines water-bearing properties of metamorphic rock and crystalline rocks, in general.

Resistivity profiling and soundings methods proved to be of little use as fissure systems could not be detected and the true thickness of the weathered and fractured zone could not be measured. Seismic refraction, instead, was quite useful to detect potential water-bearing “low velocity zones”.

Somalia

The “Bur Region” of Somalia is a large peneplain of about 30,000 km^2 with inselberg of granite and granite-gneiss rocks (“burs”), and eroded metamorphic rocks. The average yearly rainfall is 600 mm/year. The best hydrogeological conditions are along the temporarily watercourses, “wadis”, where numerous open wells tap water from alluvial deposits and weathered rocks. Water quality is generally poor but people and livestock accept it; salinity increases rapidly just at short distance from the “sand river” courses.

The irregular distribution of the water levels in wells and the rapid change in chemical composition in neighbouring wells reflect the discontinuity of these small, locally recharged, groundwater bodies. Open wells in the headwater of some streams may yield water with higher salinity than those located in the intermediate sections.

Drilling in the Bur Region has proved to be difficult and expensive as water in fractured rock can be found in small amount and often has a high salinity. The small fresh water-bearing lenses at the base of the “burs” are reliable sources for small communities during severe water shortage (Faillace 1987). Groundwater has a large variety of salinity due to the inter-relation with bordering sedimentary rocks.

Mauritania

In Western Mauritania, characterised by extremely arid conditions with a rainfall of only 100 mm/year, have been identified four main sittings favourable to occurrence of groundwater: foothill, dykes, tectonic disturbance, depression located in closed drainage (Dijon 1977). The depth of the boreholes drilled mainly in granite and gneiss rocks ranged from 15 to 70 m, an average 30-40 m. Drilling results were very poor, in Amsaga only 15% of the boreholes struck water. Borehole yield ranged between 0.05 to 2 m^3/hour. Groundwater, in most cases was highly saline. In this conditions water well drilling becomes a very expensive operation.

GENERAL CONCLUSIONS

From the overall analyses of the groundwater conditions prevailing in hard rocks covering many African countries, the following general conclusions can be drawn:

- Regional hard-rock aquifers, in most cases, do not exist,
- The groundwater occurrence is irregular and is related mainly to the weathering and fracturing of the rock and not to its composition,
- Water in fresh rock may be found in deep, isolated fissures, occasionally interconnected,
- The probability to meet water-bearing fissures decreases with depth of well,
- Borehole yield from fractured rocks is generally low, it can, however, satisfy the water requirements of small villages and for watering live-stocks,
- Well depth in hard rock may range from 10 to 100 meters,
- Promising hydrogeological conditions are located along river banks of well-defined, narrow alluvial plains where high yield boreholes may struck water-bearing alluvial deposits and thick weathered and fractured hard rock. Boreholes, open wells and infiltration galleries, are the main water sources for the irrigation of narrow alluvial riverine belts.

REFERENCES

Dijon R (1977) Ground-water exploration and development in hard rocks in Africa. International Seminar on Ground-Water in Hard Rocks, Stockholm 1977

Faillace C (1973) Location of groundwater and the Determination of the optimum depth of wells in metamorphic rocks of Karamoja, Uganda,.Proceedings of 2° congr. Intern. Sulle acque sotterranee, Palermo, Italy

Faillace C (1987) Water quality data book of Somalia.General Report, GTZ , Eschborn, Germany

Faillace C (1979) Evaluation of the rural water programme in Liberia. Internal report, UN Lir/77/004 Water Resources Policy, Management and Legislation, Monrovia, Liberia

GKW (1980) Water sector study – Report on groundwater resources, Water Supply Systems in Liberia. Unpub. Report

The Biblical story of Moses striking the rock to get water: the first report on water in fissured rocks

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The southern part of the Sinai Peninsula, Egypt is built of crystalline basement rocks, like granites and gabbros and metamorphic rocks, which are cut by acid and basic dikes. The average annual precipitation is about 80 mm. The Bedouins living in this region obtain their water by excavating wells into the alluvium filling the riverbeds and utilizing the water from the small springs issuing from the fissured crystalline rocks. They emerge on the contact between the fissured permeable and the non-permeable, namely kaolinized acid rocks along faults and contacts with dikes, or weathered gabbroitic rocks. When tne springs dry out the Bedouins dig into the fissured rocks to locate the fractures, which supplied the water to the springs. To locate dried out springs they know to trace the calcareous travertine layer deposited by the spring. When such a crust is found on a fracture in the crystalline rock, the fracture is followed to the point where the hard granite or porphyry rock is traversed by soft basic dikes, usually decomposed into clay. A shaft is then dug into the decomposed rock while care is taken to follow the fracture along the wall of the shaft. At a certain depth the water will start to seep from the fracture into the shaft. In some places, the removal of the lime travertine from the fracture is needed to enhance the flow.

These methods remind us of the Biblical story of Moses striking the rock in order to obtain water for the thirsty Children of Israel on their way to the Promised Land. Such a practice would have looked miraculous to people coming from a land where the only source of water was from the Nile, the canals and the shallow wells dug along its banks.

To my opinion the Biblical story is a distant echo on the dimension of time of some actual experiences of my ancestors in the Sinai desert. A similar echo is the incident of the bitter water of the spring of Marah ('bitter' in Hebrew), where the people of Israel arrived after crossing the Sea of Reeds. Interestingly, the water that emerges even today from the deep fossil aquifers of the Nubian Sandstone in the Sinai and Negev Deserts have a bitter taste due to the content of magnesium sulfate ($MgSO_4$ Epsom or English salt) in addition to ordinary salt (sodium chlorine) and gypsum (calcium sulfate) Thus, the description of the water as bitter provides one of the first hydrochemical reports in the history of chemistry. The lasting memory of this taste for many centuries from a place far distant from the caravan road connecting Canaan and Egypt also indicates a very ancient origin for the root of the story of this spring.

The scientific investigations of Egyptian papyree and other archaeological evidence could not, up to date, confirm the Biblical story about Moses and the story of Exodus. Yet, reading the story of the wandering of the Children of Israel through the Sinai, and especially the stories about the bitter spring, the hitting the rock to get water as well as other "environmental" incidents, pushes to the conclusion that these stories contain a factual historical core, interpreted according to ancient world view and religious beliefs as miracles by a divine force.

REFERENCE

Issar AS (1990) Water Shall Flow From the Rock, Springer Verlag

Anthropogenic effects on flow systems in fractured rocks

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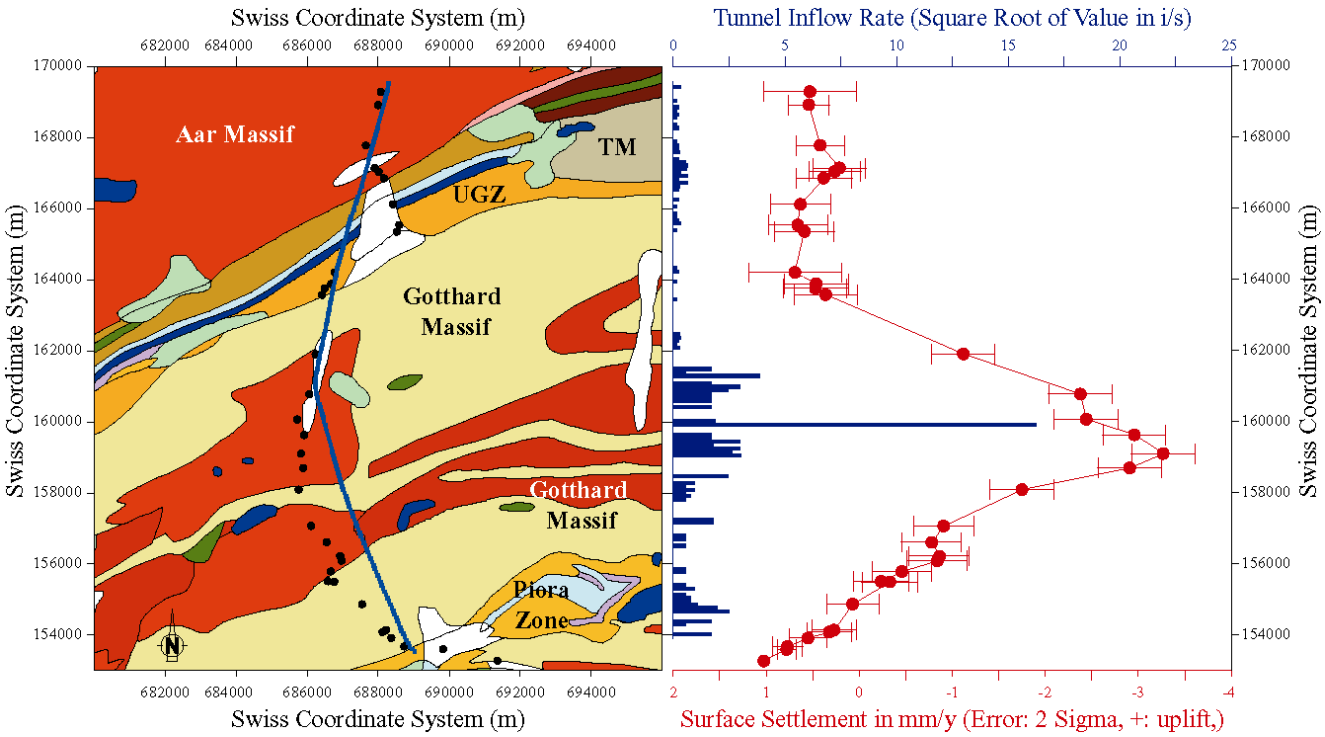
INTRODUCTION

Flow systems in fractured rocks are complex and difficult to describe. This is mainly due to the fact that the permeability distribution of fractured crystalline rocks is very heterogeneous, ranges over many orders of magnitudes, and that on many scales only few highly conductive pathways control the total groundwater flow in the rock mass (e.g. Long *et al.* 1991, Loew 2001). Fig.1 shows an example from systematic tunnel inflow measurements in the Gotthard Highway Tunnel of the External Crystalline Massifs in the Swiss Alps. In order to describe groundwater flow in such systems, highly conductive pathways must either be detected or reliably predicted (an extremely difficult task) or treated in a probabilistic framework (e.g. Raymer 2001). However, on the scale of hundreds to thousands of meters, which is the relevant scale for many practical problems (e.g. tunnel construction, petroleum engineering, geothermal energy production, deep geological waste disposal) the rock mass in-between such pathways can sometimes be approximated with equivalent continuum properties (e.g. Loew 2001).

Anthropogenic impacts on such flow systems can be described by changes in Darcy flux and advective flow direction. Such impacts obviously span a huge range both in scale and magnitude, depending on the magnitude of stress that is applied on different types of geological settings. Spatially extended and large head changes of long duration lead to strong stresses on a groundwater system; geological heterogeneity, hydraulic diffusivity, time and boundary conditions control the magnitude and extent of the resulting impact on the flow systems. For example, strong impacts on natural flow systems result from deep and unlined excavations in high permeability rock masses, whereas low level impacts result from surface excavations in low permeability environments. Fig.2 shows how a deep tunnel in crystalline rocks affects the large-scale groundwater flow system.


Swiss Coordinate System (m)
682000 684000 686000 688000 690000 692000 694000
170000 168000 166000 164000 162000 160000 158000 156000 154000
Aar Massif
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Swiss Coordinate System (m)
Tunnel Inflow Rate (Square Root of Value in i/s)
0 5 10 15 20 25
2 1 0 -1 -2 -3 -4
Surface Settlement in mm/y (Error: 2 Sigma, +: uplift,)
Swiss Coordinate System (m)

Figure 1. Geologic map of the Gotthard Highway Tunnel area (Central Alps) with geological units of the External Crystalline Massifs and the surounding metamorphic sedimentary rocks (UGZ, Piora Zone), left. Distribution of early time groundwater inflow to the Gotthard Highway Tunnel and induced surface settlements, right. The maximum vertical displacement measured since the construction of the tunnel amounts to 11 Centimeters. From Loew *et al.* 2000

The hydraulic head contours in Fig.2 are results from a 3D free surface groundwater model and are compatible with measurements performed at ground surface and in the tunnel (Ofterdinger 2001).

ANTHROPOGENIC EFFECTS: REGIONAL SCALE

Changes in groundwater head translate into fluid pressure changes that lead to modifications of effective stresses and induce substantial rock mass deformations. Such large-scale hydro-mechanically-coupled processes are well known from weak sediments, but can also be observed in hard fractured rock masses. Fig.1 (right) shows a large (10 kilometres long) settlement trough, measured at ground surface, that has developed 500 to 1000 meters above the tunnel and that was induced by the most important tunnel inflow measured along the Gotthard Highway Tunnel. Detailed investigations into the mechanisms responsible for the settlement trough above the Gotthard Highway Tunnel have shown that both the brittle fractures

(normal and shear deformation) and the elastic matrix between the fractures contribute towards surface subsidence (Zangerl *et al.* 2003). The controlling tunnel inflow corresponds to a unique fault structure in the Gotthard Massif that strikes perpendicular to the tunnel and dips steeply to the south. Even before tunnel construction, flow in that fault created a strong positive temperature anomaly (upward directed groundwater flow) which was not reversed by the draining tunnel, but instead, increased. Tritium, ^{4}He and ^{40}Ar (radiogenic) concentrations of tunnel waters sampled at the location of that fault zone indicate that these waters are very old (Lützenkirchen 2002).

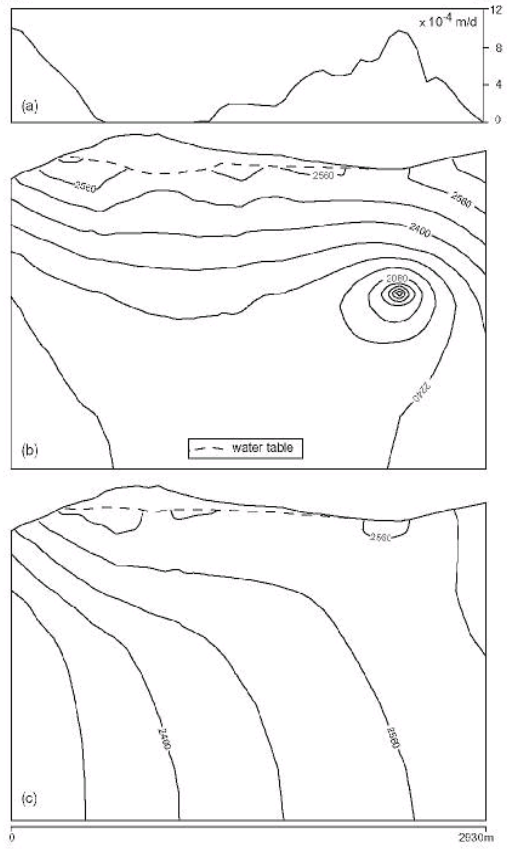

Figure 2. Distribution of hydraulic heads as derived from a 3D free-surface groundwater model in crystalline rocks without tunnel (c) and with tunnel (b). Distributed recharge at groundsurface (a) above Bedretto Tunnel in Gotthard Massif (Switzerland). From Ofterdinger (2001)

Water table drawdowns, induced by draining tunnels in such settings, can have other serious surficial impact, such as the disappearance of surface springs and wetlands as a result of a falling groundwater table (Fig.3). The behaviour of such systems has rarely been discussed in the literature and is also considered in the present paper.

ANTHROPOGENIC EFFECTS: SMALL SCALE

In low permeability settings, such as host rocks for deep nuclear waste disposal systems, head changes induced be large underground excavations are of small areal extent. But also here indirect (coupled) effects of anthropogenic impacts can be substantial. One important example are Excavation Disturbed Zones (EDZ) around drifts, caverns and shafts with hydraulic conductivities that can become several orders of magnitude bigger than the undisturbed host rock. The EDZ develops

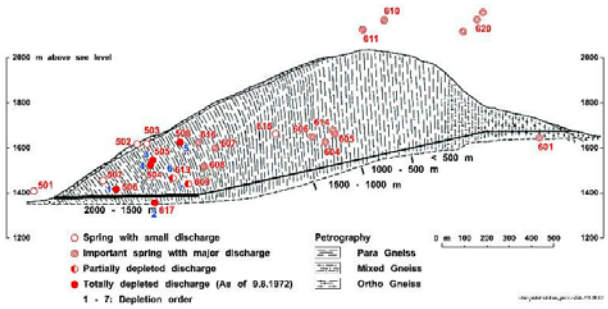

Figure 3. Surface springs projected onto the longitudinal profile of the Obergesteln drift (Gotthard Massif), differentiated by importance and degree of depletion due to drainage of the rock mass around the drift

primarily in response to the changing stress field and often contains a dense patterns of newly generated micro- and macro-fractures that connect to form conductive networks. The formation of such fractures and their properties (e.g. persistence) is influenced not only by the initial and induced stress field, but also by geological (mechanical) heterogeneities (stress concentrators) at various scales and the hydro-mechanical coupling between the intact matrix and propagating fractures. Similar processes also occur along smaller types of subsurface excavations, i.e. boreholes (skin effects).

Changes in fracture transmissivity and effective hydraulic conductivity modify advective groundwater flow and the fate of contaminants in most geological settings. The only exceptions are aquicludes where diffusive transport and osmosis dominate the transport of certain groundwater components.

REFERENCES

Long JCS, Karasaki K, Davey A, Peterson J, Landsfeld M, Kemeny J, Martel S (1991) An Inverse Approach to the Construction of Fracture Hydrology Models Conditioned by Geophysical Data. An Example from the Validation Exercises at the Stripa Mine. Int J.Rock Mech Min Sci & Geomech (Abstract) 28:121-142

Loew S (2000) AlpTransit: Engineering geology of the world's longest tunnel system. Proceedings of GeoEng2000, an international conference on geotechnical and geological engineering, Melbourne, Technomic Publishing Co

Loew S (2001) Natural groundwater pathways and models for regional groundwater flow in crystalline rocks. In: Seiler KP, Wohnlich S (eds) Proc. XXXI IAH Congress: New Approaches Characterizing Groundwater Flow. Balkema Publishers, Pp 1013-1018

Lützenkirchen V (2002) Structural Geology and Hydrogeology of Brittle Fault Zones in the Central and Eastern Gotthard Massif, Switzerland. PhD Dissertation ETH Zürich No 14749

Ofterdinger U (2001) Groundwater flow systems in the Rotondo granite, Central Alps (Switzerland). PhD Dissertation ETH Zürich No 14108

Raymer JH (2001) Groundwater inflow into Hard-Rock Tunnels. In: Tunnels and Tunnelling International, September 2001, 50-53 pp, Polygon Media, Ltd London

Zangerl C, Eberhardt E, Loew S (2003) Ground settlements above tunnels in fractured crystalline rock: numerical analysis of coupled hydromechanical mechanisms. Hydrogeology Journal 11(1):162-173

The effect of scale on the magnitude of formation properties governing fluid movement and chemical transport in fractured rock

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Abstract: Hydrogeologic problems in fractured rock often require the characterization of ground-water flow and chemical transport over distances that range from meters to 10's of kilometers. In the granite and schist underlying the Mirror Lake watershed in central New Hampshire, USA, the hydraulic conductivity of individual fractures varies over more than 6 orders of magnitude; however, the magnitude of the bulk hydraulic conductivity of the rock was the same from aquifer tests conducted over 10's of meters and kilometer-scale estimates inferred from ground-water modeling. In contrast, the magnitude of the formation properties controlling chemical migration, in particular, the dispersivity and the effective matrix diffusion, increases in comparing the results of laboratory experiments on rock samples, *in situ* tracer tests conducted over 10's of meters, and kilometer-scale estimates inferred from concentrations of environmental tracers in ground water.

INTRODUCTION

Hydrogeologic problems in fractured-rock aquifers from water supply to ground-water restoration often require characterization of ground-water flow and chemical transport over distances that range from meters to 10's of kilometers. Because of the extreme variability in hydraulic properties and the complex connectivity of fractures, formation properties that govern fluid movement and chemical transport may vary as a function of the physical dimensions of the problem. This paper investigates the magnitude of hydraulic conductivity, dispersivity and effective matrix diffusion from experiments conducted on cores, *in situ* hydraulic and tracer tests, and regional interpretations of ground-water flow and chemical transport in the igneous and metamorphic rock of the Mirror Lake watershed in central New Hampshire, USA.

MIRROR LAKE SITE

The Mirror Lake watershed has been a site of multidisciplinary and multiscale investigations of ground-water flow and chemical transport in fractured rock (Hsieh *et al.* 1993; Shapiro *et al.* 1999). In the Mirror Lake area, bedrock is overlain by glacial drift, which varies in thickness from 0 to approximately 50 meters (m). The bedrock is primarily schist that has been extensively intruded by granite. Samples of granite and schist have porosities that range from 1 to 2 percent (%) (Wood *et al.* 1996); however, fractures are the primary conduits of ground-water flow.

HYDRAULIC CONDUCTIVITY FROM METERS TO KILOMETERS

The hydraulic conductivity of fractures and the bulk hydraulic conductivity of large volumes of rock were estimated from interpretations of hydraulic tests. Single-hole hydraulic tests were conducted in over 30 bedrock boreholes using a straddle-packer apparatus to isolate closely spaced fractures in boreholes (Shapiro and Hsieh 1998). The hydraulic conductivity of fractures as estimated from the single-hole tests ranges from the detection limit of the *in situ* equipment, which is approximately 10^{-10} meters per second (m/s), to 10^{-4} m/s (Shapiro and Hsieh 1998).

Hsieh and Shapiro (1996) and Hsieh *et al.* (1999) conducted several multiple-hole hydraulic tests by pumping water from a packed-off interval of one bedrock borehole and monitoring the fluid pressure in drift piezometers and packed-off intervals in bedrock boreholes distributed over approximately a hectare. The interpretation of these tests indicated that highly permeable fractures form subhorizontal zones that have lateral dimensions of 20-50 m; however, the fractures that comprise these zones are not subhorizontal. The zones of highly permeable fractures are connected hydraulically through a network of less permeable fractures. The network of less permeable fractures controls the bulk hydraulic conductivity of the rock, which is approximately 10^{-7} m/s, about 3 orders of magnitude less than the hydraulic conductivity of the most permeable fractures in the rock volume.

Over approximately 16 square kilometers (km^2) in the Mirror Lake area, the bulk hydraulic conductivity of the rock was estimated using a regional ground-water flow model. The measured hydraulic head in bedrock boreholes and piezometers in the glacial drift, and the measured ground-water discharges to streams were used for model calibration (Tiedeman *et al.* 1998). The bulk hydraulic conductivity of the bedrock from the regional ground-water flow model was the same order of magnitude as the bulk hydraulic conductivity as estimated from aquifer tests that affected approximately a hectare. This indicates that conductive fractures are not controlling ground-water flow over dimensions of the watershed, and the bulk hydraulic conductivity of the rock in the Mirror Lake area does not change as a function of the problem scale (Hsieh 1998).

DISPERSIVITY AND MATRIX DIFFUSION FROM CORES TO KILOMETERS

Dispersivity is a measure of the variability in the fluid velocity affecting the advection of dissolved constituents in ground water (Gelhar *et al.* 1992), and matrix diffusion is usually described as the process by which dissolved constituents diffuse into or out of the primary porosity of the rock. In general, the diffusion coefficient for a nonsorbing species in the primary porosity of the rock is described by the following equation,

$$D = n_{rm}\, \alpha\, D_w = n_{rm}\, D_{rm}$$

where D is the formation diffusion coefficient, n_{rm} is the primary porosity of the rock, α is a formation factor related to the tortuosity and interconnectivity of the primary porosity, D_w is the diffusion coefficient of the dissolved constituent in water, and D_{rm} is the effective diffusion coefficient of the dissolved constituent in the rock. The dispersivity and the effective matrix diffusion were estimated from the interpretation of controlled laboratory and field-scale tracer tests, and the interpretation of concentrations of environmental tracers in ground water.

In diffusion experiments conducted in samples of granite and schist from the Mirror Lake area, Wood *et al.* (1996) used Cesium-137 (^{137}Cs) as a tracer. ^{137}Cs is highly retarded; however, once the retardation was considered, the effective diffusion coefficient, D_{rm}, was similar in magnitude to results of tracer tests conducted in similar types of rock (Ohlsson and Neretnieks 1995). In general, D_{rm} varies from 10^{-13} to 10^{-11} square meters per

second (m^2/s). In the rock matrix, there is no ground-water flow, thus, chemical diffusion is the only mechanism for chemical migration, and dispersion is not considered.

Tracer tests were conducted between bedrock boreholes under hydraulically stressed conditions by pumping from a packed-off interval in one borehole and injecting a tracer solution into a packed-off interval in a nearby borehole (Shapiro 1996; Becker and Shapiro 2000). The tracer tests were conducted in a highly permeable subhorizontal zone intersected by multiple boreholes. Interpretation of these tracer experiments showed that the dispersivity was approximately 10% of the distance between the boreholes, and estimates of the effective diffusion coefficient, D_{rm}, were at least equal to or greater than the coefficient of diffusion for the dissolved constituent in water, which is several orders of magnitude larger than estimates of D_{rm} from the laboratory experiments conducted on rock samples.

In general, D_{rm} should not be greater than the diffusion coefficient of the dissolved species in water; however, for the *in situ* tracer experiments D_{rm} was estimated to provide a best fit with the measured tracer concentrations at the pumped well. The large effective matrix diffusion is hypothesized to be an artifact of the extreme variability in the hydraulic properties of the fractures (Shapiro 2001). Advection from highly permeable fractures to low permeability fractures results in chemical advection over a short distance in an extended period of time, before reemerging into a highly permeable fracture again. This process is analogous to a dissolved constituent diffusing into and out of an immobile fluid (such as that in the rock matrix), and thus, the process is analogous to diffusion (even though it stems from the variability in the fluid advection).

Over distances of kilometers, the concentrations of environmental tracers measured in ground water were used to estimate the transport properties in the bedrock. Shapiro (2001) interpreted the concentrations of tritium (^3H) and dichlorodifluoromethane (CFC-12) in water samples collected from packed-off intervals in bedrock boreholes and piezometers in the glacial drift throughout the Mirror Lake area. Shapiro (2001) showed that, D_{rm} was at least 10^{-8} m^2/s and the dispersivity was approximately 100 m, which is a fraction of the travel distance of regional scale transport. The large effective matrix diffusion over travel distances ranging from 100's of meters to kilometers is again hypothesized to be an artifact of the extreme variability in the hydraulic properties of the fractures (Shapiro 2001).

CONCLUSIONS

Estimates of hydraulic conductivity in fractured rock over increasingly larger dimensions can provide insight into the connectivity of highly permeable fractures. At the Mirror Lake site in central New Hampshire, USA, the bulk hydraulic conductivity of the rock does not appear to increase from interpretations covering 10's of meters to kilometers. In contrast, the dispersivity and the effective matrix diffusion that control chemical migration increase as a function of the problem dimension. The formation properties that characterize processes of chemical migration are dependent on the variability in the fluid velocity. Over distances of 10's of meters to kilometers, there appears to be an increasing degree of variability in the fluid velocity.

REFERENCES

Becker MW, Shapiro AM (2000) Tracer transport in fractured crystalline rock—Evidence of nondiffusive breakthrough tailing: Water Resources Research 36(7):1677-1686

Gelhar LW, Welty C, Rehfeldt KR (1992) A critical review of data on field-scale dispersion in aquifers. Water Resources Research 28(7):1955-1974

Hsieh PA (1998) Scale effects in fluid flow through fractured geologic media. In: Sposito G (ed) Scale Dependence and Scale Invariance in Hydrology. Cambridge University Press, Cambridge UK:335-353

Hsieh PA, Shapiro AM (1996) Hydraulic characteristics of fractured bedrock underlying the FSE well field at the Mirror Lake site, Grafton County, NH. In: Morganwalp DW, Aronson DA (eds) US Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Colorado Springs, CO, September 20-24, 1993: US Geological Survey Water-Resources Investigations Report 94-4015:127-130

Hsieh PA, Shapiro AM, Barton CC, Haeni FP, Johnson CD, Martin CW, Paillet FL, Winter TC, Wright DL (1993) Methods of characterizing fluid movement and chemical transport in fractured rock. In: Chaney JT, Hepburn JC (eds) Field Trip Guidebook for Northeastern United States, v 2: Geological Society of America, Boulder, CO:R1-R30

Hsieh PA, Shapiro AM, Tiedeman CR (1999) Computer simulation of fluid flow in fractured rocks at the Mirror Lake FSE well field. In: Morganwalp DW, Buxton HT (eds) US Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999-Volume 3 of 3-Subsurface Contamination from Point Sources: US Geological Survey Water-Resources Investigations Report 99-4018C:777-781

Ohlsson Y, Neretnieks I (1995) Literature survey of matrix diffusion theory and of experiments and data including natural analogues. Swedish Nuclear Fuel and Waste Management company (SKB), Stockholm, Technical Report 95-12, 89 pp

Shapiro AM (1996) Estimation of effective porosity in fractured crystalline rock by controlled-tracer tests. In Stevens P.R. and Nicholson TJ (eds) Joint US Geological Survey, US Nuclear Regulatory Commission on Research Related to Low-Level Radioactive Waste Disposal, May 4-6, 1993, National Center, Reston, Virginia, Proceedings: US Geological Survey Water-Resources Investigations Report 95-4015:185-190

Shapiro AM (2001) Effective matrix diffusion in kilometer-scale transport in fractured crystalline rock. Water Resources Research 37(3):507-522

Shapiro AM, Hsieh PA (1998) How good are estimates of transmissivity from slug tests in fractured rock? Ground Water 36(1):37-48

Shapiro AM, Hsieh PA, Haeni FP (1999) Integrating multidisciplinary investigations in the characterization of fractured rock. In: Morganwalp DW, Buxton HT (eds) US Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Charleston, South Carolina, March 8-12, 1999-Volume 3 of 3-Subsurface Contamination from Point Sources: US Geological Survey Water-Resources Investigations Report 99-4018C:669-680

Tiedeman CR, Goode DJ, Hsieh PA (1998) Characterizing a ground water basin in a New England mountain and valley terrain. Ground Water 36(4):611-620

Wood WW, Shapiro AM, Hsieh PA, Councell TB (1996) Observational, experimental and inferred evidence for solute diffusion in fractured granite aquifers: Examples from the Mirror Lake watershed, Grafton County, NH. In: Morganwalp DW, Aronson DA (eds) US Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Colorado Springs, CO, September 20-24, 1993: US Geological Survey Water-Resources Investigations Report 94-4015:167-170

Fractured Rock Aquifer-Analogue: research concept and project implementation

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A b s t r a c t : A research initiative, funded by the German Science Foundation (DFG), was launched in 1996 to investigate flow and transport processes in fractured rocks. The research concept is based on the so called ´Aquifer-Analogue´ approach which involves that well defined samples from sandstone outcrops (quarries) of different formats are assumed to constitute realistic representations of aquifer material generally not accessible except for a few boreholes. Various direct (e.g. hydraulic, pneumatic) and indirect (e.g. geophysical) investigation methods have been applied at various scales. Based on the corresponding parametrisation, physically based lumped and distributed parameter models were developed and validated.

INTRODUCTION

Flow and transport processes in fractured rocks are very difficult to describe quantitatively at field scale. Due to the geometrical irregularity of the joints, fissures and fractures, the high hydraulic conductivity contrast between fractures and rock matrix and the generally higher monitoring costs, only very few well documented sites exist. The majority of these sites has been instrumented for the purpose of identification of suitable nuclear waste repositories and they are consequently located in low to very low permeability (mostly crystalline) rocks.

However, fractured rock systems forming relevant aquifers show some very different characteristics. Frequently, consolidated sand-, silt- or claystones with multiple (fracture-) porosity features prevail. The hydraulic conductivity is generally much higher than in crystalline rocks and the original sediment layering as well as the diagenetic cementation may both affect the distribution of the effective porosity as well as hydraulic conductivity. However, most of the existing subsurface investigation and hydrogeological assessment techniques were designed for well conductive unconsolidated aquifers and a few techniques (e.g. fluid logging) were developed to work in low permeability environments. There is in fact no appropriate concept or technique available for the characterisation of materials with medium range permeability, i.e. multiple-porosity systems commonly encountered within thick sedimentary beds.

PROJECT STRUCTURE

In order to investigate the principle features of such systems a research initiative, funded by the German Science Foundation (DFG), was launched in 1996 and is now in its seventh year. This initiative is led by the University of Tübingen and supported by research groups from the Universities of Aachen, Karlsruhe and Stuttgart. While the emphasis of the Tübingen and Karlsruhe groups is mainly on the design of appropriate and adapted experimental techniques at the laboratory and field scale concentrate the Stuttgart and the Aachen groups on the development of suitable modelling tools using discrete and continuum approaches.

PROJECT CONCEPT

The research concept is based on the so called ´Aquifer-Analogue´ approach (Fig.1), which implies that well defined samples from sandstone outcrops (quarries) were used as realistic representation for those sections of the (aquifer) system where access is limited to (a few) boreholes. Flow and transport properties of fractured porous sandstone materials were determined at different scales and appropriate measuring techniques were developed. We used samples with dimensions of between ca. 0.05 m (cores) and 10 m (field block) in length to investigate the main features of the system, i.e. the relative influence of the fractured system as compared to the properties of the permeable porous matrix on the flow and transport behaviour. We designed various direct (e.g. hydraulic and pneumatic) and indirect (e.g. geophysical) investigation methods in order to parameterise the system adequately. Resin casting techniques for example were employed to discretely determine fracture dimensions at the core scale, gas flow and gas transport tomographical experimental set-ups were used to evaluate the three-dimensional properties of large-scale (1 m³) laboratory samples. Diffusivity (K/S) investigations showed to be extremely useful to emphasise the hydraulic conductivity contrast between fractures and permeable matrix and to categorise the samples. Inverse techniques allowed the determination of the equivalent continuum three-dimensional anisotropy tensor of the hydraulic conductivity from the experimental data i.e. the estimation of equivalent parameters. The above experimental methods were also employed on the field block allowing estimates on the effect of the scale of investigations on the estimates of flow and transport properties. Based on these parameters various physically based distributed and lumped parameter models were developed to analyse the experimental data and also to predict the outcome of future experiments (experimental design). These model approaches included a stream tube model that demonstrated to be very efficient and useful for the interpretation of the experimental results but also multi-phase discrete fracture flow and transport models, capable to simulate the actual physical processes. Double continuum model investigations assisted in identifying the simplest equivalent model that could represent the experimental data and phenomenological observations, such as fracture geometries.

For some scenarios we were able to conduct independent model validation exercises and used those to relatively rank the modelling concepts employed.

Details about experimental and modelling approaches and methodologies as well as results can be found in companion papers in this issue, i.e. McDermott *et al.* (2003), Brauchler *et al.* (2003a, b), Suess *et al.* (2003), Hase *et al.* (2003), Vogel *et al.* (2003), and Hötzl *et al.* (2003).

REFERENCES

Brauchler R, Leven C, Dietrich P (2003a) Multivariate statistical approach for characterizing flow and transport, this issue

Brauchler R, Liedl R, Dietrich P (2003b) Identification of the diffusivity distribution by using a new hydraulic tomographic approach derived from travel time tomography, this issue

Hase M, Vogel T, Lagendijk VR, Köngeter J (2003) A statistical approach to build up a multi-continuum model describing flow and transport processes in fractured permeable sandstone, this issue

McDermott CI, Sauter M, Liedl R, Teutsch G (2003: Streamtube model used to define anisotropic tensors describing tomographical three dimensional gas flow and transport within fracture networks at a laboratory scale, this issue

Suess M, Eichel H, Helmig R (2003) The verification and the further development of a method for the determination of the spatial distribution of heterogeneities based on numerical simulations, this issue

Vogel T, Hase M (2003) Applying the multi-continuum approach to experimental data of tracer experiments in fractured permeable sandstone, this issue

Weede M, Lambert M, Hötzl H (2003) Experiments on flow and transport processes in fractured porous media in dependence on fracture and rock permeability, this issue

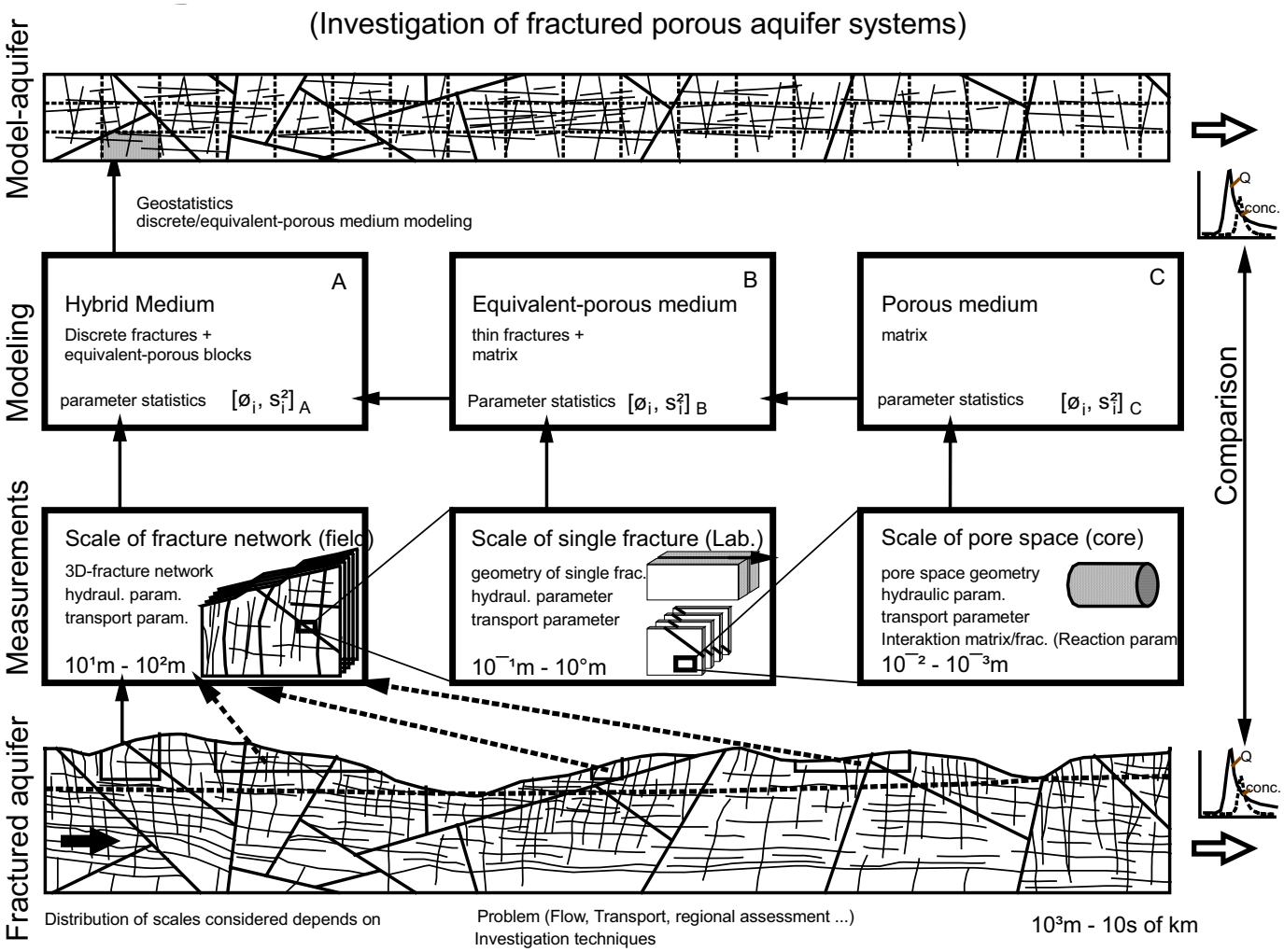

Figure 1. Aquifer Analogue Approach

TOPIC 1

HYDROGEOLOGIC ENVIRONMENT OF FRACTURED ROCKS

- Geometry and anatomy of hydrogeologic bodies
- Spatial distribution of hydraulic parameters
- Geologic features: discontinuities, fractures, barriers, aquicludes - hydrogeologic consequences
- Regional and synthetic studies
- Case studies

Summary of hydraulic conductivity measurements and differences between different methods in boreholes KR1 – KR10 at Olkiluoto, Finland

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A b s t r a c t : Traditionally, hydraulic conductivity has been measured using double-packer injection test with constant head or long-term pumping test. A new method, difference flow logging (difference flow meter), has been introduced. In the flow meter measurement, the test section is isolated from the rest of the borehole with a set of flexible rubber discs and the drawdown is kept constant along the entire borehole by pumping. In fracture zones and in their vicinity double-packer injection test gives often a clearly higher value of hydraulic conductivity than difference flow logging or long-term pumping test. Local overpressure used in HTU tests and the rather short injection time together with fracture network properties are the most probable explanations for the observed differences. Also, the possible short-circuits between the test section and borehole contribute to differences in measured conductivity. HTU- and difference flow logging results agree better in averagely fractured rock.

MEASUREMENTS

Two main methods have been used to measure hydraulic conductivity in deep boreholes at Olkiluoto Island:

- constant head injection test with double-packers (later HTU – Hydraulic Testing Unit) (e.g. Kuusela-Lahtinen *et al.* 1991 Hämäläinen 1997)
- difference flow loggings (difference flow meter) (e.g. Pöllänen and Rouhiainen 1996a,b, Rouhiainen 2000)

In addition, long-term pumping tests have been performed in some fracture zones (Ylinen and Väätäinen 1993, Jääskeläinen 1998).

In the beginning of site investigations 1990, only the HTU-tool was available. Measurements usually commenced at a depth of 100 m, as the uppermost 40 m of the boreholes was normally cased and some of the boreholes were cemented down to 100 m to stabilise the boreholes and to enhance the flushing water circulation during drilling. Borehole sections, 31 m and occasionally 7 m long, were isolated from the rest of the borehole with double packers. Mainly 200 kPa overpressure with one hour pumping and one hour recovery periods was used.

Since 1996, mainly difference flow meter has been used (Öhberg and Rouhiainen 2000). The method is known as difference flow logging and either normal flow logging mode or the detailed flow logging mode can be used. The difference flow meter measures flow into or out from the test section without introducing any pressure difference between the test section and the rest of the borehole. The borehole water can flow through the tool via bypass tube. The test section is isolated with a set of flexible rubber discs and the drawdown is kept constant along the entire borehole by long-term pumping (from 1 to 10 days) or keeping the water level in the borehole at the "natural" level. Two different hydraulic head and flow values are needed to interpret the hydraulic conductivity and the hydraulic head around the test section accurately. If the distribution of the head along depth is known in advance, one flow value is enough. This technique is used normally when detailed flow logging mode is applied.

The improved HTU-tool has also been used to measure mainly the very low hydraulic conductivity, which the flow meter is not capable to detect. Typical injection and recovery period since 1997 have been from 15 to 30 min and mainly 200 kPa overpressure has been used.

Mostly 2 m measuring sections have been used for both tools. In detailed flow logging, 0.5 m section length is used.

By the end of 2002, in total over 800 test sections (2 m) were measured with the HTU-tool and around 6000 with the difference flow meter at the Olkiluoto site. In addition, transmissivity of six major fracture zones has been determined on the basis of long-term pumping tests.

COMPARISON OF RESULTS BETWEEN METHODS

Hydraulic conductivities for all methods were calculated according to the radial flow equation

$$K = \frac{Q}{2\pi L \Delta h} \ln(r_0 / r_w)$$

where equal radius of effect (r_0) of 14 m was used to simplify the interpretation and the comparison of results.

Hydraulic conductivities are converted to transmissivities to make the comparison between different methods and section lengths easier. As an example, the results of hydraulic conductivity measurements using the HTU and difference flow logging methods as well as one T-value of fracture zones between 100-150 m based on long-term pumping tests (Ylinen 1993, Jääskeläinen 1998) in borehole KR1 are presented in Fig.1.

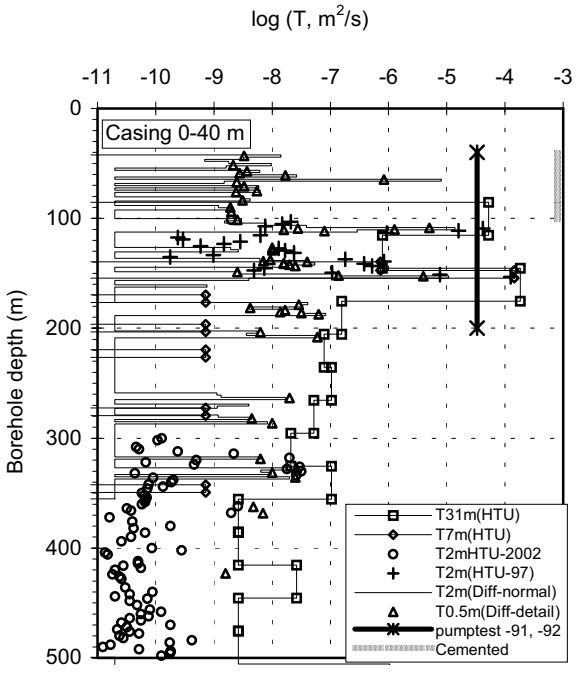

Figure 1. Measured transmissivities by different methods in borehole KR1 at depth interval of 40-500 m

First, the results from the long-term pumping test sections were compared with each other, see Fig.2. As can be seen in Fig.2, the HTU-tool with 2 m test section gives always the highest conductivity. Also the 31 m HTU-values are often higher than the values measured by long-term pumping test and flow logging.

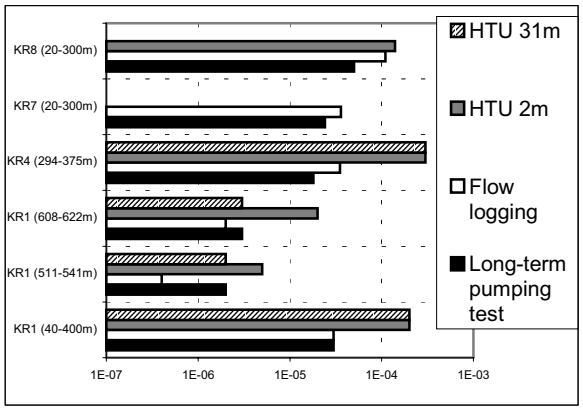

Figure 2. Transmissivities of some major fracture zones measured by different methods

Fig.3 shows the results from borehole KR2 divided in two groups, averagely fractured rock and fracture zones (including 20 m around them). In the averagely fractured rock, the HTU- and difference flow logging results are in accordance. In fractured sections HTU-values are on average two to three times higher than the values observed in flow loggings.

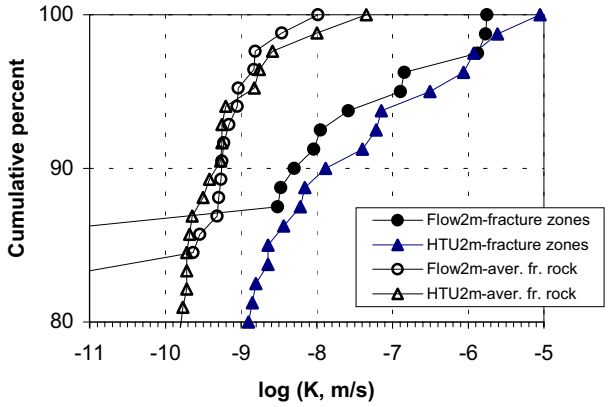

Figure 3. Cumulative distribution of hydraulic conductivities measured by HTU and difference flow meter in borehole KR2, divided to averagely fractured rock and fracture zones (+20m) (Ahokas 2001)

Summary of all results measured by difference flow meter and HTU is presented in Fig.4, where the results are divided to averagely fractured rock and fracture zones (+10 m around). Results measured by HTU in fracture zones are averagely five to six times higher than values obtained by difference flow meter. In averagely fractured rock the values agree better. For the values less than –9 the comparison is not valid e.g. due to the different measuring limits of the methods

CONCLUSIONS

In fracture zones, the double-packer injection test (HTU) often gives a higher value of hydraulic conductivity than the difference flow logging or a long-term pumping test. Local overpressure used in HTU tests, rather short injection times, and fracture network properties are the most probable explanations for the observed differences. Also, possible short-circuits between test sections and the borehole may contribute to differences in the interpreted conductivity. In those fracture zones where results are in accordance, fractures are assumed to be parallel to the zone orientation and the flow during the tests is radial resulting in similar values of hydraulic conductivity. This is also the case mostly in the averagely fractured rock where the results of different methods are usually similar.

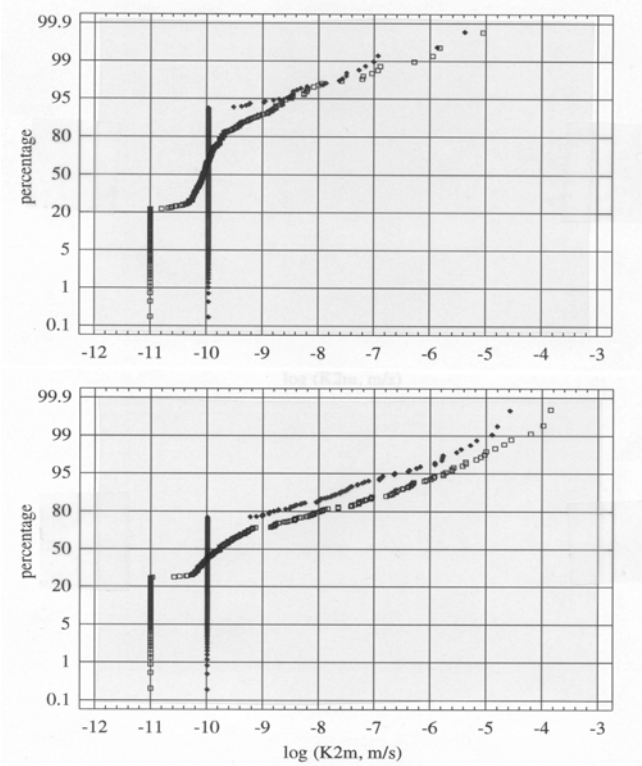

Figure 4. Normal probability plots of hydraulic conductivities measured by HTU and difference flow meter at Olkiluoto divided to averagely fractured rock (above) and fracture zones (+10m, below)

REFERENCES

Ahokas H (2001) Summary of results of measurements of hydraulic conductivity and differences between different methods in boreholes KR1 - KR10 at Olkiluoto (in Finnish with an English abstract). Helsinki, Finland: Posiva Oy 109 p Working report 2001-33

Hämäläinen H (1997) Measurements of hydraulic conductivity at Olkiluoto in Eurajoki, borehole OL-KR1 (in Finnish with an English abstract). Helsinki, Finland: Posiva Oy 476 p. Working Report 97-03 (Vol 1 and 2)

Jääskeläinen P (1998) Pumping tests in boreholes KR1 and KR4 at Olkiluoto in the winter 1998. Working Report 98-76. Posiva Oy, Helsinki (in Finnish with an English abstract)

Kuusela-Lahtinen A, Front K (1991) Single Borehole Hydraulic Tests in Olkiluoto, Western Finland: Interpretation of Borehole KR1 (in Finnish with an English abstract). Helsinki, Finland: Teollisuuden Voima Oy p.TVO/Site investigations Work Report 91-25

Pöllänen J, Rouhiainen P (1996a) Difference flow measurements at the Olkiluoto site in Eurajoki, boreholes KR1-KR4, KR7 and KR8. Site Investigation Project, Work report 96-43e. Posiva Oy, Helsinki

Pöllänen J, Rouhiainen P (1996b) Difference flow measurements at the Olkiluoto site in Eurajoki, boreholes KR9 and KR10. Site Investigation Project, Work report 96-44e. Posiva Oy, Helsinki

Rouhiainen P (2000) Electrical conductivity and detailed flow logging at the Olkiluoto site in Eurajoki, boreholes KR1-KR11. Working Report 99-72. Posiva Oy, Helsinki

Öhberg A, Rouhiainen P (2000) Posiva groundwater flow measuring techniques. Helsinki, Finland, Posiva Oy. 81 p. POSIVA 2000-12

Ylinen A, Väätäinen A (1993) Interpretation of the 1989-1992 hydraulic interference tests at the five TVO sites in Finland. Report YJT-93-10. Nuclear Waste Commission of Finnish Power Companies, Helsinki

Contribution to the understanding of crystalline systems as aquifers: the experience of the State of Paraíba, northeast Brazil

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A b s t r a c t : Crystalline aquifer systems are prevailing over 95% of the huge semiarid region of the State of Paraíba in north-eastern Brazil. A great number of water wells have been drilled over this area during the last century. However, the level of understanding about the aquifer systems as a whole, up to now, remains far from the desirable. This paper discusses the main aspects and features on this subject, in terms of nature, dimension, basic parameters and hydraulic behaviour of the fractured zones. Some new data and recent information are presented, product of many years of methodical observations.

INTRODUCTION

The State of Paraíba, in the easternmost part of the Brazilian shield (fig.1), has an area of ca. 56 300 Km^2, 95% of which under semiarid conditions, with rainfall rates between 300 and 800 mm/year (600 mm/year as average), mostly concentrated in February-May period.

Figure 1. Location of the State of Paraíba in Brazil

Most of its area (ca. 49 000 Km^2) is formed by gneisses and migmatites (basement "massifs") and some fold belts of meta-volcano-sedimentary assemblages. Only 4 540 Km^2 are occupied by sedimentary rocks.

General geomorphological features of a dissected tablelands are predominating, with highest altitudes around 1190m (Jabre summit). Five major hydrographic river systems characterise the State: Piranhas, Paraíba, Curimataú, Jacú and Mamanguape.

CRYSTALLINE ROCKS AS AQUIFER SYSTEMS

As usual, crystalline rocks of massifs and Proterozoic fold belts display only secondary porosities formed by different fractures, in terms of both nature and shape. Groundwater is stored and could present some circulation only along these fractures, with good connections with the hydrological cycle. This depends upon morphological factors (such as lowlands, valleys, river streams) and on the possibility of the net of fractures to accomplish reservoirs with some permeability. Under these conditions, they tend to be discontinuous and heterogeneous systems, with volumetric dimensions very difficult to be determined, a challenge even for most of the geological geophysical research methods. Particularly, the problem of deepness of the fracturing system constitutes an open question. This information is necessary to define the dimensional characteristics of subsurface reservoirs of all kinds. In spite of the difficulty of making abstractions such as the so-called "representative volume element", very usual when dealing with aquifer systems of sedimentary rocks, the crystalline rocks actually behave as aquifer systems, naturally divided in different hydrographic basins, the best units for quantitative and qualitative analysis. Actually, they represent a modest amount of water resources as a whole, available only in special conditions of fair-producing fractured zones, which would be better named as *hydraulic conductors*, according to Gustafson and Krasny (1994), and Manoel Filho (1996), or as *aquifer zones,* according to Albuquerque (1984).

THE DIMENSIONAL MODEL OF THE HYDRAULIC CONDUCTOR OR AQUIFER ZONE

This model was developed based upon the studies and experience of the author during the last 40 years, using statistical analysis and field observations, mainly on extensional tectonics. About 6000 water wells were drilled in the State of Paraíba, 75% of them with some useful information both on water resources and drilling features. The analysis presented hereafter is based only on information from 2850 wells considered trustful, presenting pumping tests of at least 12 hours, and dynamic level of the pumping test positioned above the deepest water entrance (the deepest known fracture).

The principal dimensional data utilised was the magnitude of the fractured surfaces (length and width) and their deepness. These linear features in the ground surface – somehow followed by the drainage – have by far been observed from regional geology, aero-photo interpretations and with support of geophysical studies. Actually, these linear features, used as guidance for water well locations, are the surface strike of the hydraulic conductor itself.

The depth of the fracturing is commonly a matter of dispute. Some close association between depth of fractures and depths of the fracture zones has been done, but this is an equivocal procedure according to our observations. The water entrances are – according to our model – adventitious connecting fractures, some of them from paleotectonic tensional origin, different of those of the main crystalline reservoir of groundwater, which are of extensional and modern character.

A statistical analysis of these water entrances was performed, according to hydrographic basins, for the whole semiarid area of the State of Paraíba. For different basins there was no noteworthy feature. Generally, the most productive water entrances are in the depth interval between 10 and 20 m (about 40% of the whole amount), with decreasing values of depth, following an arithmetic progression, close of ½ reason.

The proposed model of aquifer zones attends the regional geomorphological and hydrological history and the neotectonics. According to this model, the main body of the fissured reservoir has only rarely been reached by the drill holes. Mostly, the drillers have intercepted adventitious and accessory fractures, through which the groundwater flows to the well hole.

WELL HYDRAULICS OF AQUIFER ZONES

The acquisition of hydrodynamic parameters is a hard task and a challenge. Manoel Filho (1996) has developed a new method for calculating hydraulic parameters from the heterogeneous and complex aquifers systems. This "method of the fractal specific capacity" is based on the Chaos Theory and on the concept of Fractals. In the State of Paraíba, 20 production tests were analysed, resulting in the following average values: 5.78 10^{-3} m^2/s for transmissivity, 10^{-2}% to 10^{-4}% for porosity and 10^{-2} to 10^{-6} m/s for permeability. Reiterating Manoel Filho, it is difficult to evaluate by now the meaning of these values, because of the small number of tests. Anyhow, this kind of method is promising.

THE HYDROLOGICAL BEHAVIOUR

This behaviour is concerned with the relationships between the aquifer zones (hydraulic conductors) and the hydrological cycle, particularly with the small water streams that are superposed to them. These relationships are materialised in terms of the natural processes of recharge, circulation and discharge.

According to our studies, in the high courses of the Paraíba River, the recharge is done only during the rainy period, when a minor part of the runoff is lost by infiltration. This information is obtained by limnigraphs, positioned in tubular wells, located at the margins of creeks controlled by fractures (so-called "riachos-fendas" in Brazil). Such recharge should be facilitated and conducted by a veneer of alluvial deposits (1 to 2 m thick). The natural flow along the sub-horizontal plane is probably developed only during the recharge period under the command of the water stream (superposed to the aquifer zone), and so, this should be done from the high to the low course. As far as the rainy period finishes, the fluvial runoff is also finished, and for this reason most of the creeks are ephemeral.

The decrease of the hydraulic head, as shown by the observations of the water level, probably is due to the evapotranspiration losses occurred in the dry season. The increase in the values (about 40% up) of total dissolved solids (TDS) on water during the dry season confirms this assumption.

The discharge is performed only by the hydrographic network superposed to the aquifer zone, i.e., superposed to the hydraulic conductors of the whole aquifer zone. Such discharge is null during the years of insufficient recharge, when the hydraulic heads do not reach levels above those of the thalwegs of the creeks.

QUANTITATIVE EVALUATION

Three different components of the aquifer systems should be considered: potential, reserves and availabilities. The potential is given by the mean long-term base discharge. For the case of crystalline systems, the potential is not significant.

The reserves are given by the sum of volumes of groundwater stored in the interior of all aquifer zones that constitute the system. This component of the groundwater resources remains as an unknown term, because it has not been possible up to now to define the depth of each hydraulic conductor, as well as the availabilities. The latest, on present days, are quantified by the yield of water wells, keeping in mind the expectation/risk of complete exhaustion, either due to the high rates of pumping or due to the lack of sufficient annual recharge. Such availabilities reach 49.93 10^6 m^3/year, taking in account the present yield of 2432 water wells, with an average yield of 2.32 m^3/h.

QUALITATIVE EVALUATION

Only 3020 wells present some reasonable data on the chemical character of the groundwater, specially records about TDS, which were used in this study as the parameter of analysis for different hydrographic basins (Tab.1), following as close as possible the criteria of ABNT (Brazilian Association of Technical Regulation) and of WHO (World Health Organisation): TDS values less than 1500 mg/L are good for human consumption; between 1500 and 6000 mg/L are appropriate for cattle consumption, and TDS greater than 6000 mg/L are not appropriate for any kind on consumption (unless after desalination).

Tab.1 shows that only in the Piranhas River Basin there are a great number of wells appropriate for human consumption. To the eastern part of this basin, along the sub-basins of Espinharas and Sabugi Rivers, where the annual rainfall rates are between 800 and 600 mm, there are wells with TDS over 6000 mg/L. Likewise, in the hydrographic basins of Jacu/Curimataú and Paraiba Rivers, mainly in their eastern portions (where there are the highest annual rain fall rates, 800-600 mm/year), occurs TDS over 6000 mg/L. The same is true for the western portion of the Mamanguape River basin. At the western part of the Paraíba River basin, the annual rainfall rates are lower than 600 mm, but the values of TDS are less than 1500 mg/L.

The reason for such heterogeneity is naturally associated to other variables of hydro-climatic, morphologic and lithologic characters, which carry influence on the chemical weathering of rocks, such as the relative air humidity, the relief of peneplains (which makes the drainage difficult), as well as the susceptibility of mineral components to the action of weathering agents. In terms of observation in different periods, there are some indications that the salinity uses to decrease with the recharge (with pluvial periods) as well as it is common some increase in the salinity during dry seasons.

CONCLUSIONS

The reserves, the most significant part of the groundwater resources of the crystalline aquifers, remain unknown, either at the scale of zone or at the scale of aquifer system, due to the difficulties in quantifying the fractures dimensions.

The hydrological behaviour of the aquifer zones shows that part of the reserves, also unknown, is annually lost by evapotranspiration during the dry season and recharged by the fluvial runoff during the rainy season. The other part of the reserves seems not to be linked to the hydrological cycle. The natural horizontal circulation appears to exist only episodically and in a small amount.

The spatial variability of the water quality is very high and does not present correlation with rainfall rates, depending upon hydro-climatic, morphologic and lithologic factors.

REFERENCES

Albuquerque JPT (1984) Groundwater resources in the semiarid tropics of the State of Paraíba, Brazil. MSc Dissertation, Federal University of Paraíba, Campina Grande, 183 pp

Manuel Filho J (1996) A Fractal Dimension model for evaluation of hydraulic parameters in fissural aquifers. Doctoral Dissertation, São Paulo University, São Paulo, 197 pp

Table 1. Distribution of values of TDS by hydrographic basin

Hydrographic Basin	Total Dissolved Solids – TDS – mg/L									
	– 500		500 – 1000		1000 – 1500		1500 – 6000		6000 –	
	Nº	%	Nº	%	Nº	%	Nº	%	Nº	%
Piranhas	343	27.2	471	37.3	239	18.9	153	12.1	57	4.5
Paraíba	28	2.1	117	8.7	128	9.5	700	51.7	379	28.0
Mamanguape	21	8.5	23	9.3	32	12.9	95	39.5	77	31.0
Jacu/Curimataú	2	1.4	8	5.7	12	8.5	58	41.1	61	43.3

Hydrogeology of fractured dolomite reservoir: Devonian reef complex, Volgograd Region, Russia

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This study integrates geological data, geophysical log, hydrodynamic and tracer investigations to characterise the Upper Devonian carbonate reservoir of the Pamyatno-Sasovskoe oilfield, Volgograd Region, Russia. This oilfield is located in the northern part of the Volgograd Region, 300 km northwest of Volgograd. This is the principal reservoir between the numerous platform margin reef build-ups and it differs from other by concentrating reefs of different ages in the common thickness of 800 m. Reef reservoir consists of Frasnian fractured-dolomites and it is overlain by the relatively impermeable Famenian shales and limestones. The off-reef basin facies are shaly limestone, which overlap against the reef. The length of structure is 16 km and the width of the upper part of reservoir is about 1 km.

Hydraulic network of carbonate rocks consists of three types of spaces: pores, caverns and fissures and all these types are present in the reservoir. Detailed petrophysical analysis generally includes an estimate of porosity, permeability, oil and water saturation in the matrix. Porosity and permeability values, based on core plug analysis, have been used for the cross-plot of porosity versus permeability (fig.1). This is a usual picture for carbonate reservoirs where a wide scatter of data points deteriorates correlation. According to these data the porosity for the most of samples are in the range 0.5-8%, the estimated effective porosity is 7,4%.

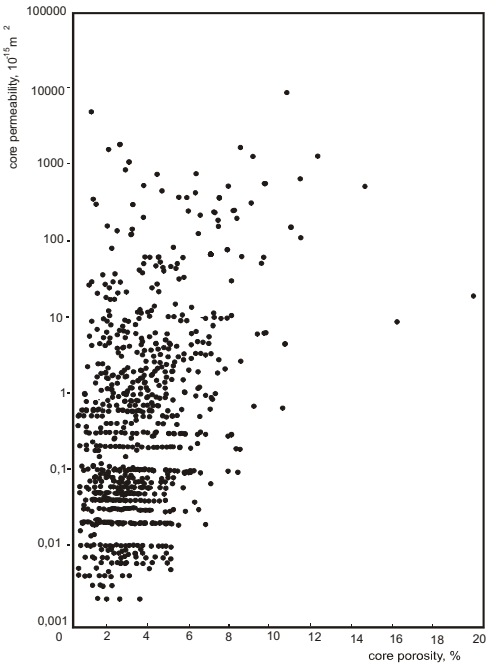

Figure 1. Porosity vs. permeability scatter plot for the productive reservoir, Pamyatno-Sasovskoe oilfield

Core measurements take into account pores and microcaverns. Large caverns and fissures can be detected during the drilling process: increasing penetration rate, drilling instrument falling (up to 4 m), and losses of mud circulation. These voids can be taken into account also by test investigations. It has been postulated that all parts of the reservoirs are well communicated through vertical fractures and along horizontal high permeability zones.

Predicting permeability is the most difficult task facing the reservoir analyst as the log data, core measurements and test results do not provide a complete record of the permeability throughout the volume of the reservoir, especially in highly heterogeneous formations. The method to model permeability on the coarse scale presents the combination of the borehole radon indication and tracer investigation. Such a model has been built for the carbonate reef reservoir.

The method of radon indication has been used in many wells. The permeability along the vertical section in the well can be calculated according to the level of radioactivity on the log after injecting radon. For one of the wells injection rate profile along the well log is shown in fig.2. For every well the limited narrow zones with very high transmissivity can be detected along the productive reservoir.

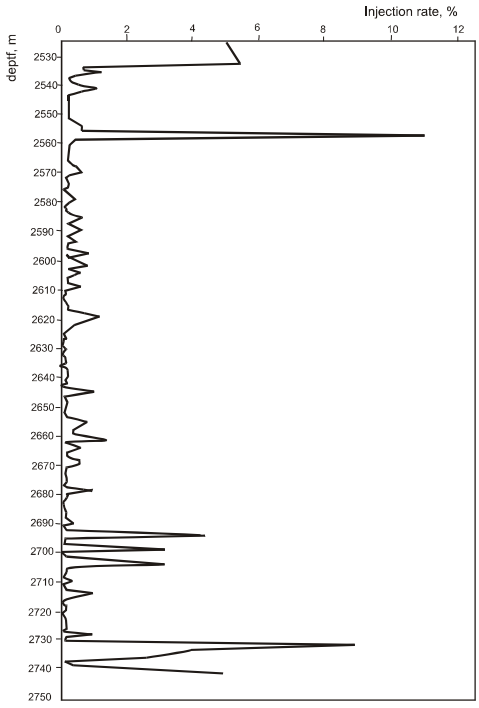

Figure 2. Relative transmissivity profile for reef reservoir

Tracers (tritium and different chemical substances) have been used to collect reservoir data about velocity, concentration and frequency of presented tracers. Dissolved tracers have been pumped in the injection wells and water samples from productive wells were detected for tracers. These investigations show that there is a fractured high-permeable zone in the axial part of structure where the velocities of tracers are up to 1000 m/day. Local hydraulic conductivity of these fissures is very large. Such high velocities prove also the low volume and high piezo-conductivity of these fractures. These zones are characterised by the high concentration of tracers and low frequency of their detection (fig.3a). In contract, the zones with high porosity show the low concentration of tracers and presence of them in the main part of samples (fig.3b).

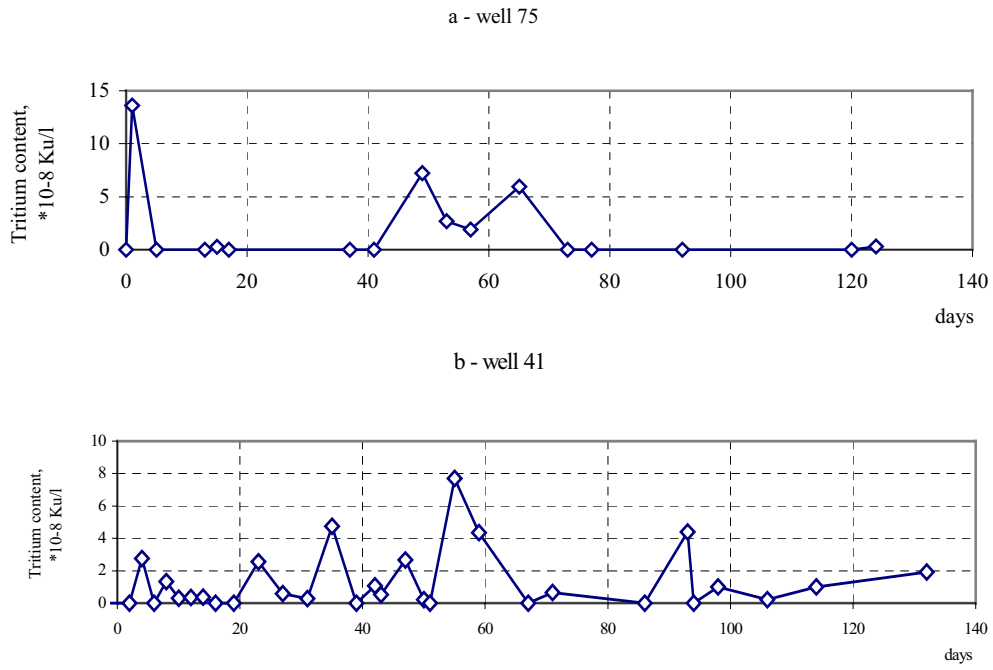

Figure 3. Tracer measurements obtained in the abstraction boreholes

High velocity of tracer along the axial part of structure gives a basis to propose the linear flow from the single-well injection test. Under these conditions the equivalent aperture of the main fracture may be calculated as

$$b = Q/2vh$$

where Q – pumping rate of the well, 1000 m^3/day
v – natural water velocity, 1000 m/day
h - height of the main fissure, 800 m
Equivalent aperture of the fissure is 0.006 m

Development of the oilfield creates such process as decreasing the formation pressure. Taking into account the oil and water abstraction, volumetric compressibility of oil and water and decreasing rate of formation pressure the volume of reservoir has been calculated. The relationship between oil and water saturated zones has been postulated as 1/15. These investigations help to present the more adequate model of the complex carbonate reservoir with the elongated axial fissure (fig.4).

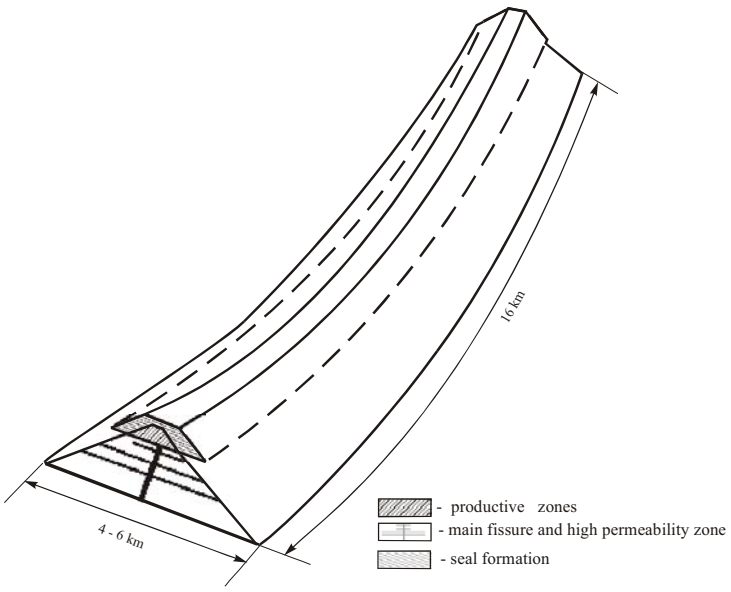

Figure 4. Geological model of the reef carbonate reservoir

Hydrogeological and hydrochemical conditions of a deep groundwater system in the Yuseong granitic rock area, Korea

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A b s t r a c t : Six deep boreholes were drilled to obtain hydrogeological and hydrochemical data at Jurassic granites in the Yuseong area, Korea. The core observation, televiewer logging and hydraulic testing were carried out during and after drilling and multi-packer system was installed in a 500 m deep borehole for hydraulic and hydrochemical monitoring including environmental isotopes. According to integrated data, the geoenvironment is supposed to be divided into two regimes such as upper and lower with a boundary at 200~250 m below ground surface. These could be defined as fractured and massive in fracture characteristics, hydraulically active and low flow zone in physical hydrological aspect, and oxidizing and reducing zone in hydrogeochemical considerations. The integration of hydrogeochemical and hydrodynamic data provided better confidence for understanding of groundwater system in fractured rock mass. It could be possible to suggest a general guideline to develop the disposal concept of high-level radioactive waste including performance assessment at current status in Korea.

The Korea Atomic Energy Research Institute (KAERI) is in charge of conducting the research program of High Level Radioactive Waste (HLW) disposal in Korea. The main tasks of geoscientific study were focused mainly on a near-field condition of deep geological environment for the reference disposal system of HLW at the current stage in Korea. It was also aimed to define and produce the geologic input data including neotectonic features, rock fracture systems and mechanical properties of plutonic rocks, hydrogeological and hydrogeochemical characteristics of groundwater.

As a part of the research program, six boreholes (250 m ~ 500 m in depth) were drilled to obtain the hydrogeological and hydrochemical data from a Jurassic granite in the Yuseong area, located about 100km south of Seoul, that was suggested as one of the preferred host rock types for HLW repository in Korea. The core observation, televiewer logging and hydraulic testing were carried out during and after drilling, and the multi-packer (MP) system was installed in a 500 m deep borehole for hydraulic and hydrochemical monitoring including environmental isotopes. The groundwaters in the borehole were isolated to 14 sections by packers according to depth and fracture system.

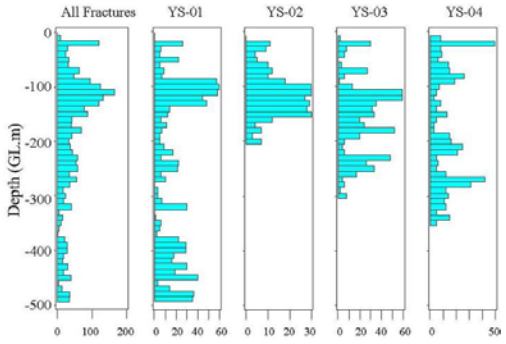

Figure 1. Variation of the fracture frequency per every 10 m along the depth in boreholes of Yuseong area

Highly fractured zone in the boreholes was observed around 104 m and 400 m below surface (Fig.1) and was collapsed after the drilling and hydraulic testing. Based on the data from all boreholes, the fractures in the boreholes consisted of three sets (vertical, sub-vertical and one sub-horizontal) in direction and shows 4/m in frequency. The spacing of conductive fractures could be calculated as 9.6 m, 11.0 m and 142 m for each set of fractures, respectively. The aperture size of fractures is distributed in a lognormal distribution pattern with the geometric mean of 2.34 mm. A number of impermeable zones are also confirmed in the borehole and the hydraulic conductivity of the conducting zones reaches to about $1x10^{-7}$ m/s. The effective hydraulic conductivity of the upper and lower parts ranges $5.2x10^{-10}$ m/s ~ $8.6x10^{-10}$ m/s and $2.4x10^{-10}$ m/s ~ $5.9x10^{-10}$ m/s. It is considered that these ranges result from a difference between the steady and transient state analysis (Tab.1; KAERI 2002).

Table 1. Summary of effective hydraulic conductivities and statistics using constant injection test and fall-off test in the study site (x10-10 m/s; Ks & Kt steady & transient state analysis)

	All data		Upper zone		Lower zone	
	K_s	K_t	K_s	K_t	K_s	K_t
K_G= K_E	3.5	7.2	5.3	7.6	2.5	6.8
K_A	3.1	201	424	303	221	88
K_H	1.0	0.2	0.1	.04	0.08	0.1
Median	2.5	5.8	3.1	5.2	1.3	7.2
Max.	9870	5760	9740	5760	9870	2140
Min.	0.01					

Field measurements including temperature, pH, redox potential, electrical conductivity, dissolved oxygen and alkalinity of groundwater were carried out. Since the installation of MP system on Sep. 2001, the groundwater was sampled and analyzed seven times. Although the groundwater from the open boreholes before MP installation was monitored, the data are not included in this report. The geochemistry indicated lots of differences between before and after the installation MP system. The thermal gradient is 0.26°C/100 m obtained from measurement by the MP probe at the groundwater sampling depth, which is almost duplicated during each measurement. The grouting activity, affecting groundwater quality, was inevitably carried out before the MP installation on the zone with Portland cement.

The groundwater of the section affected by grouting has abnormally high pH (12.7), whereas the pH value of groundwater of 200 m below surface reaches almost constant value as about 10.0 (Fig.2). The redox potential of groundwater varied with depth and more negative values were recognized in deep groundwater. Except the section affected by grouting materials, the concentrations of Na, Ca, Mg, K, Cl, HCO_3 and SO_4 of groundwater are almost constant below GL –200 m. Fluorine in deep groundwater shows high concentration up to 12.7 mg/*l* and tends to increase with depth, indicating that water-rock interaction increases with depth.

The Portland cement ($CaO{\cdot}SiO_2{\cdot}Al_2O_3{\cdot}Fe_2O_3$) was used for grouting with sodium and potassium silicates for fast hydration.

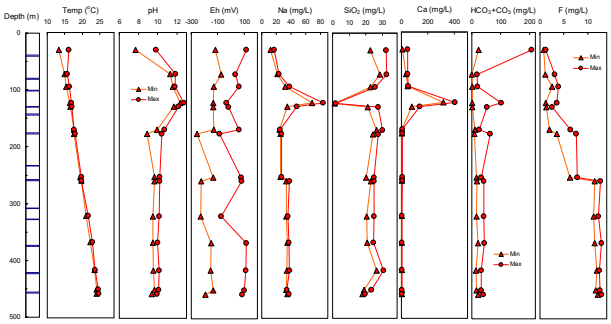

Figure 2. Variation of geochemical data along the depth in the borehole with MP system

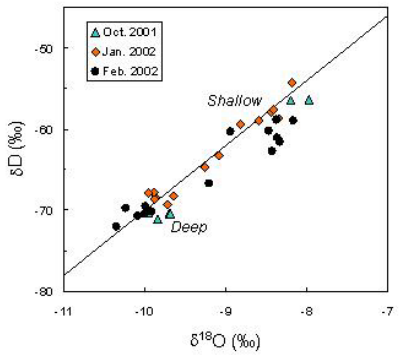

Figure 3. The relationship of δ18O and δD diagram of water samples for the borehole. Worldwide meteoric water line is shown

The main reaction of groundwater with the cement is hydration, which pH increases and also Na, K and Ca are released to groundwater. Consequently, the groundwater shows chemically Ca-OH type. Although the alkalinity was measured and C content of the high pH groundwater was calculated, it is uncertain to compute total dissolved carbonate from pH and alkalinity, since these two parameters are chiefly controlled by the concentration of hydroxyl ions.

Although the chemical characteristics of natural shallow groundwater were not identified from the borehole, due to the grouting, the geochemical data of shallow groundwater in the vicinity of the borehole can be used for the comparison with deep groundwater. Surface water and shallow groundwater mainly reacted with soil shows Ca-HCO_3 type or Ca-Na-HCO_3 type, whereas deep groundwater below 250 m from the surface belongs to typical Na-HCO_3 type. Although the tracer, like urine, was not used for drilling fluid, the variations of geochemical data of groundwater with time shows whether the groundwater is stabilized after drilling and the installation of MP system. It shows that field parameter and chemical compositions were stabilized to natural state within 6 months after the installation of MP system. According to the monitoring data using MP system and analyzed such as hydraulic head and geochemical compositions, it is considered as slightly downward flow or nearly lateral flow condition. The period for stabilization of geochemical conditions is related to the properties of groundwater flow along the fractures.

The $\delta^{18}O$ and δD values are nearly plotted along the worldwide meteoric water line (Fig.3), which is indicating that groundwater from the borehole was recharged from local meteoric waters under present climate conditions. It is noteworthy that isotopic compositions of deep groundwater are lighter than those of surface and shallow groundwater in the borehole of Yuseong area. It is likely that deep groundwater was recharged from the area of higher elevation. Considering the altitude effect (0.19‰/100 m, $\delta^{18}O$) of isotope from precipitation in Korea (Kim and Nakai 1988), the recharge area of the deep groundwater is estimated to high elevations than the local land surface. Tritium contents close to zero are observed in the deep groundwater, thus confirming a long residence time of deep groundwater. On the other hand, high tritium values characterized in the shallow groundwater are considered as recent waters with a very short circulating time. The tritium content of the intermediate section is 5.4 to 6.7 TU, indicating that the residence time of the groundwater is less than 50 years or the mixing process between old water and local young water prevails.

The carbon isotope data show the contribution of carbon from either the microbial oxidation of organic matter or carbon dioxide from plant respiration. The $\delta^{34}S_{SO4}$ values indicate that the dissolved sulfates of the groundwater may be originated from sulfide minerals. However, it is not ruled out the contribution of anthropogenically derived sulphur from higher $\delta^{34}S$ values of shallow groundwater. The ^{14}C analysis (27.5~58.9 pmC) was carried out by AMS, indicating the residence time of the deep groundwater is about 4,000~6,000 yrs BP according to chemical and isotopic calibration.

According to the mentioned integrated data, the geoenvironment is supposed to be roughly divided into two regimes such as upper and lower with a boundary at 200~250 m below ground surface. These could be defined as fractured and massive in fracture characteristics, hydraulically active and low flow zone in physical hydrological aspect, and oxidizing and reducing zone in hydrogeochemical considerations (Fig.4). There is no significant unstable condition in rock mechanical consideration according to the stress ratios with depth, but it has been confirmed to show a linear and stable variation from 150~200 m in depth.

These results that integrated hydrogeochemical and hydrodynamic data provided better confidence for understanding of groundwater system in fractured rock mass. In this way, it could be possible to suggest a general guideline to develop the disposal concept of high-level radioactive waste including performance assessment at current status in Korea.

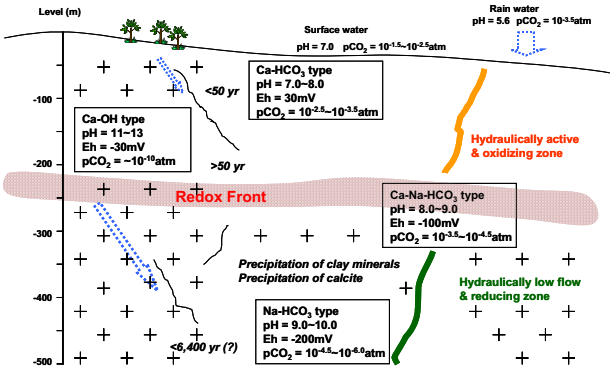

Figure 4. Estimated geoenvironmental condition for reference disposal concept of HLW in Korea

REFERENCES

Korea Atomic Energy Research Institute (2002) A progress report of the geoscientific research on plutonic rock mass for a HLW disposal in Korea, KAERI/TR-2266/2002, 166 pp

Kim KH, Nakai N (1988) Isotopic compositions of precipitations and groundwaters in South Korea. Jour Geol Soc Korea 24:37-46

Hydrogeology of granite rocks in Sardinia (Italy)

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The granite rocks of Sardinia are mainly represented by muscovite-biotite- and biotite granites, granodiorites, aplites, and their frequent microgranular, porphyritic and pegmatitic varieties. The granite bodies are often intersected by swarms of microgranite and lamprophyre dikes. They generally belong to the crystalline basement of Sardinia and Corsica, which from the late pre-Cambrian to the present time has been affected by all the geodynamic events which occurred in the Mediterranean basin, namely the Caledonian, Hercynian, and Alpine orogenesis. The crystalline basement, consisting of granite and metamorphic rocks of Precambrian and Palaeozoic age, partially covered with Mesozoic, Cainozoic and Recent deposits, was faulted in depth, to form the major Campidano Graben, also opening up several secondary tectonic troughs on both sides (Ciminale *et al*. (1985); Cocozza and Jacobacci (1975); Egger *et al.* (1988); Montaldo *et al*. (1971); Pala *et al.* (1982 a, b); Pecorini and Pomesano Cerchi (1969).

The granite rocks make up the northern and north-central part of the south-eastern corner of Sardinia. Other important outcrops are present in the south-western part and along the eastern coast. On the whole, they are related to the Caledonian and especially to the Hercynian orogenesis. Observations on the relations between the different lithotypes inside the granite bodies have suggested to the author the hypothesis that the granite bodies might have been somehow reactivated during different orogenic phases.

Because of the Alpine upfaulting and downfaulting of the different tectonic blocks, the physiography of the crystalline basement was rejuvenated by a strong denudation. At present, it is characterized by massifs partly weathered, mostly rounded, and almost flat-topped, often separated by deep and intractable valleys. The slopes are covered with screes, and piedmont deposits border their heels in the valleys and tectonic troughs.

Preliminary hydrogeological surveys carried out in the early Seventies indicated that the granites in Sardinia first underwent plastic deformation during their intrusion, prior to being completely crystallized, and subsequently become post-crystalline ruptural deformations (Barrocu and Larsson 1977; Montaldo *et al.* 1974). The local interest for this type of investigation is evident if we consider that the hard rocks, mainly consisting of granites, make up about one quarter of the total surface of Sardinia, i.e. about 6,000 Km^2 out of 23,833 or 24,089 Km^2, including the small coastal islands.

The hydrogeological investigations carried out in several areas concerned, consisted mainly of an assessment of the geological, petrographical, and geomorphological problems, structural analysis (field studies and photogeological interpretation), geophysical investigations, drilling operations, logging and test pumping, and hydrochemical analysis. The findings demonstrate that groundwater in granite rocks in Sardinia may occur in 1. fracture zones; 2. weathered zones of the rock and 3. microgranite dikes.

Structural analysis proved to be a valid method for determining the rock local fracture pattern. In reality, when looking for groundwater in hard rocks, the structural model may be much more complicated than expected, especially if the granite bodies have been affected by several phases of post crystalline deformations. Tensional, shear and overthrust fractures were recognized as having been produced by different lateral stresses related to the different tectonic phases that affected Sardinia during the Caledonian, Hercynian, and Alpine orogenesis (Barrocu and Larsson 1977).

Openness of fractures strongly depends on fracture types, being maximum along the tensile cracks and the overthrust zones. It is also strongly influenced by the effects of weathering and hydrothermal alteration. The dimensions of the aquifers may be limited by the presence of lamprophyre dikes, consisting of hornblende-plagioclase-spessartite with a little interstitial orthoclase and quartz. They are generally strongly weathered in depth, so that they act as underground barriers between contiguous granite sectors. In areas where these dikes frequently occur, granite aquifers may have good hydraulic conductivity but their storage capacity is poor. The closer together the dikes (it does not seem important if they are only a few centimetres thick), the fewer the possibilities of having a good aquifer. In this case the granite aquifers may have a good hydraulic conductivity but their storage capacity is low (Barrocu and Vernier 1975).

Wells are generally drilled down to 50÷80 m, but fresh groundwater is found down to a few hundred metres. In south-western Sardinia, in a tunnel of an old molybdenite mine, a constant fresh groundwater yield of 4.0 L/s was measured at -700 m in a shear zone crossing several tension fractures (Barrocu and Vernier 1971).

In northern Sardinia, in an area with an average annual rainfall of more than 1,000 mm, in dry summers several wells drilled in a great shear zone crossing several granite sectors acting as their drain gave a maximum yield of 2.1 L/s (7,500 m^3/h). Systematic *in situ* and laboratory investigations were carried out, aiming at finding correlations between fracturation parameters, geomechanical characteristics, and permeability data measured down to -50 m (Barrocu and Manca 1979).

Several wells drilled in different semi-confined aquifers in weathered granite down to the bedrock, -15÷17 m deep, yielded 0.5÷.3 L/s (1,800÷8,300 m^3/h) in different periods in 1975-77. A transmissivity $T=1.37x10^{-4}÷1.67x10^{-4}$ m^2/s and a storativity S=0.33÷0.49% were calculated. Assuming an aquifer of total thickness D=0.5 m, a conductivity value of $K=T/D=(2.74÷3.34)x10^{-4}$ m/s was estimated. In southern Sardinia, where the average annual rainfall is lower that 500 mm, transmissivity values $T=8x10^{-6}÷3x10^{-5}$ m^2/s and storativity values S=0.3÷2.2% were calculated by applying the Theis, Jacob and Cooper, and Chow methods in a major tension fracture zone draining smaller cracks. In the fine fractures the transmissivity ranged between $1.5x10^{-6}$ and $4.0x10^{-6}$ m^2/s and the storativity between 0.15 and 0.8% (Rosén 1977). In central Sardinia, where the average annual rainfall is 800 mm, in rather tight shear fractures a storativity of 0.05% was estimated, i.e. 1/10 of the value found in tension fractures in southern Sardinia. This figure corresponds to a bed storativity of about 4,000÷7,000 m^3/Km^2. The several wells drilled yielded between 0.10 and 0.86 m^3/h, the specific capacity being $4.1x10^{-2}÷2.9x10^{-2}$ m^2/h.

So far, the results of the investigations carried out confirm the reliability and validity of a geomechanical approach on a local scale. They demonstrate that in certain cases fracture zones and microgranite dikes might be usefully sealed off at their outlet, so as to form fairly good groundwater reservoirs. In others, where rainfall is not very abundant and especially not well distributed throughout the year, it can happen that yield is fairly high immediately after a rainfall event but then decreases because the groundwater finds its way into the sea.

The granite rocks of Sardinia may represent a valuable source of groundwater for farms and small villages in the countryside and for tourist resorts along the coast. Aquifers in granite rocks may provide a valid contribution to solving local water supply

problems. However, it should be essential that the exploitation of these water resources be scientifically controlled in terms of safe yield.

Major faults control thermal water circulation, with a downward movement schematically interpreted as a multi-cell system governed by piston flow and a relatively faster upward movement due to gas pressure (Loddo *et al*. 1982; Panichi 1982).

Mixing of shallow groundwater with the deep saline water is marked by increasing TDS, decreasing Ca/Mg ratios, Na–Cl dominant character, and higher concentrations of B, and Sr. The Na/Cl ratios are close to values observed in seawater; and Cl, Na, K, B, and Sr show high correlation coefficients, supporting an origin from a diluted, modified seawater (Caboi *et al.* 1986; 1993)

The origin of thermal waters salinity can be attributed chiefly to sea level fluctuations during geologic history, especially during the Quaternary. Marine water saturated the deep fractures of the crystalline basement and is presently re-mobilised by circulating fluids (Zuppi *et al*. 2002).

REFERENCES

Barrocu G, Vernier A (1971) Acque nella miniera di Perd'e Pibera (Sardegna sud-occidentale). In: Proc. Int. Sym. on Groundwater in Crystalline Rocks. Cattedra di Geologia Applicata Fac Ing Univ Cagliari 142-149

Barrocu G, Vernier A (1975) Notizie preliminari sulla idrogeologia di alcuni filoni di porfido in rocce granitiche della Sardegna. III Conv Int Acque Sott Palermo Nov 1975. In: Atti Cattedra di Geologia Applicata Fac Ing Univ Cagliari 1-9

Barrocu G, Larsson I (1977) Granite tectonics at groundwater prospection in southernmost Sardinia. In: Geohydrological Investigations of Groundwater in Granite Rocks in Sardinia. Dept Land Impr Drain, R Inst Techn Stockholm, II 3:21A:3-27

Barrocu G, Manca PP (1979) Geomechanical characteristics of a granite body at a dam site. In: Proc Int Symp IAEG on Eng Geol Problems in Hydrotechn Construction, Tbilisi, URSS - Bull IAEG 20:32-35

Caboi R, Cidu R, Fanfani L, Zuddas P (1986) Geochemistry of thermal waters in Sardinia (Italy). In: Proc 5th Int Symp WRI Reykjavik, Iceland, August 8-1, 1986

Caboi R, Cidu R, Fanfani L, Zuddas P, Zanzari AR (1993) Geochemistry of the high-pCO_2 waters in Logudoro, Sardinia, Italy. Applied Geochemistry 8:153-160

Cataldi R, Mongelli F, Squarci P, Taffi L, Zito G, Calore C (1995) Geothermal ranking of Italian territory. Geothermics 24 (1):115-119

Ciminale M, Galdeano A, Gibert D, Loddo M, Pecorini G, Zito G (1985) Magnetic Survey in the Campidano Graben (Sardinia): description and interpretation. Boll Geof Teor Appl 27:221-235

Cocozza T, Jacobacci A (1975) Geologcal outline of Sardinia. In Geology of Italy. The Earth Science Soc of the Lybian Arab Rep, Tripoli, II:49-81

D'Amore F, Fancelli R, Caboi R (1987) Observations on the application of chemical geothermometers to some hydrotermal systems in Sardinia. Geothermics, 16(3):271-282

Egger A, Demartin M, Ansorge J, Banda E, Maistrello M (1988) The gross structure of the crust under Corsica and Sardinia. Tectonophysics 150:363-389

Loddo M, Mongelli F, Pecorini G, Tramacere A (1982) Prime misure di flusso di calore in Sardegna. In: Ricerche Geotermiche in Sardegna con particolare riferimento al Graben del Campidano. PFE-RF 10, CNR-Rome 181-209

Montaldo P (ed) (1971) Proc Int Symp on Groundwater in Crystalline Rocks Cattedra di Geologia Applicata Fac Ing Univ Cagliari, 171 pp

Montaldo P *et al* (1974) Geohydrological Investigations of Groundwater in Granite Rocks in Sardinia. Dept Land Impr Drain, R Inst Techn Stockholm, I 3:15:1-74

Pala A, Pecorini G, Porcu A, Serra S (1982 a) Schema geologico strutturale della Sardegna. In: Ricerche Geotermiche in Sardegna con particolare riferimento al Graben del Campidano. CNR-PFE-SPEG-RF10, CNR-Pisa 7-24

Pala A, Pecorini G, Porcu A, Serra S (1982 b) Geologia e idrogeologia del Campidano. In: Ricerche Geotermiche in Sardegna. CNR-PFE-SPEG-RF10, CNR-Pisa 87-103

Panichi C (1982) Carta delle temperature sotterranee. CNR-PFE-RF 10, CNR Roma

Pecorini G, Pomesano Cerchi A (1969) Ricerche geologiche e biostratigrafiche sul Campidano meridionale (Sardegna). Mem Soc Geol It 8:421-451

Rosén B (1977) Subsurface hydrology. In: Geohydrological Investigations of Groundwater in Granite Rocks in Sardinia, Dept Land Impr Drain, R Inst Techn Stockholm, II, 3:21A:69-82.

Zuppi GM, Sacchi E, Lombardi S, Quattrocchi F, Guerra M, Pizzino L, Angelone M (2002) Fluid geochemistry throughout the Sardinian Rift-Campidano Graben: the seismic quiescence of geochemically «active» fault systems. In preparation.

Flow heterogeneity in the fractured Chalk aquifer of southern England

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A b s t r a c t : The aim of the current work is to investigate the heterogeneity of flow in the Chalk aquifer of southern England. The rock mass properties and hydraulic characteristics of the aquifer have been characterised using a suite of geological and geophysical surveys and hydraulic tests. Fracture logs have been produced based on core logging and using optical images of boreholes. Flow has been characterised using borehole flow logs and dilution tests and hydraulic conductivity measured using packer tests. Fractures have been recorded with apertures in the range <1mm to about 30cm (sub-karstic enlargement) in diameter, however, hydrogeologically significant flow is not restricted to the enlarged fractures and is affected by the local groundwater head distribution. The work is being undertaken as part of the LOCAR Programme. LOCAR is a multi-project programme with the aim of measuring and modelling processes controlling water and material fluxes within lowland permeable catchments in the UK.

BACKGROUND TO THE STUDY

The Chalk aquifer is important because it sustains most of the surface waters, and consequently, freshwater habitats, throughout large parts of southern England and the Paris Basin, and understanding the distribution of flow in the aquifer is therefore central to the sustainable management of Chalk lowland catchments. Flow in the Chalk aquifer is known to be highly heterogeneous over a range of scales and uncertainties arising from heterogeneous flow in the aquifer have significant implications for water resource management at borehole to catchment scales (Allen *et al*. 1997). In addition, an understanding of flow heterogeneity in the aquifer is of great importance for groundwater source protection (van Leeuwen *et al.* 1998), and for our ability to predict the movement and fate of contaminants in the Chalk.

The heterogeneity of flow is a function of the fracture distribution, particularly the preferentially enlarged component of the fracture network (Bloomfield 1996), and of groundwater head distributions in the aquifer (Price 1987). Hydraulic tests, including pumping, borehole packer, and tracer tests can be used to obtain effective values for hydraulic conductivity and storage at a borehole or site scale, however it is not trivial to extrapolate these observations to larger scales given the nature of flow heterogeneity in the Chalk.

Modelling studies of flow in UK Chalk aquifers usually use a continuum approximation, where the fractured rock mass is replaced by an equivalent porous medium. Parameter values for such models (e.g. hydraulic conductivity) are generally obtained through analyses of aquifer pumping tests. Such an approach carries the implicit assumptions that the aquifer not only behaves as a continuum at the scale of the test, but that it also behaves as the same continuum on the catchment scale. In fact, as the flow in the Chalk occurs almost entirely through discrete fractures and these fractures are highly heterogeneous over a range of scales, it is unlikely that these assumptions are valid. Consequently, there is a need to better understand flow heterogeneity in the Chalk aquifer and to be able to predict the nature of flow heterogeneity on the basis of often relatively sparse data, up to the catchment scale. More specifically, there is a need to link an understanding and interpretation of flow in the Chalk using the discrete fracture approach on a local scale with catchment scale continuum methodologies.

This paper describes field investigations into the relationship between fracture distributions and groundwater flow distributions in the Chalk aquifer at two sites in the Pang-Lambourn catchment in southern England. The work is part of the LOCAR Programme, a programme aimed at

- developing an improved understanding of hydrological, hydrogeological, geomorphological and ecological interactions within permeable catchment systems, and their associated aquatic habitats, at different spatial and temporal scales and for different land uses
- developing improved modelling, database and GIS tools to inform and support the integrated management of lowland catchment systems

Details of the LOCAR Programme can be found at the following web site (http://www.nerc.ac.uk/funding/thematics/locar).

SITES AND FIELD STUDIES

Field data has been collected using an integrated suite of geological and geophysical surveys and field hydraulic tests at two sites, Frilsham Meadow and Trumpletts Farm. Both these sites are located in the Pang catchment on the Chalk aquifer about 80 km west of London. The site at Trumpletts Farm is located on an interfluve while the Frilsham Meadow site is located next to the River Pang, a small tributary of the River Thames. Eight boreholes were drilled (rotary with air flush) at Frilsham Meadow and seven were drilled at Trumpletts Farm. Of these boreholes one was cored at each site. Typical drilled depths were in the range 40 to 100 metres below ground level (mbGL). It was necessary to case most of the boreholes down to about 18 mbGL to prevent collapse of the borehole in the upper interval.

Lithological and fracture logs were prepared using the core. In addition, digital optical imager logs were run on each borehole and fractures in the boreholes were picked from these logs to obtain orientation information. A suite of geophysical logs was obtained for each borehole including gamma, resistivity, temperature and electrical conductivity. In addition impeller flow logs were produced under static and pumped conditions. Following geophysical logging three boreholes at Frilsham Meadow and one borehole at Trumpletts Farm were left open for hydraulic testing, the remaining boreholes were completed as piesometers. Borehole dilution tests were undertaken on the open borehole at Trumpletts Farm. These were performed by filling the borehole with a weak brine solution and monitoring the dilution of the salt column within the borehole due to flow under both natural groundwater gradient conditions and while a neighbouring public supply borehole was pumped. Following the borehole dilution test eleven packer tests were performed on the same borehole, over intervals of 2 to 3 metres. These tests were used to characterise the hydraulic conductivity profile in the borehole.

RESULTS

Fracturing at the sites is typical of bedded Chalk. There are three predominant fracture sets present, one joint set parallel to the sub-horizontal bedding and two fracture sets at high angles to bedding. Fracture density reduces in a non-linear manner with increasing depth, with the top 10 metres of the Chalk typically consisting of a Chalk gravel. The optical imager logs show the most enlarged fractures to be associated with sub-karstic development at the intersections of faults, particularly near the base of the weathered Chalk at about 20 to 30 mbGL, and to a lesser extent along isolated fractures parallel to bedding planes in the deeper, intact Chalk.

The graph on the right hand side of Fig.1 shows the location of joints and faults in a typical borehole at Frilsham Meadow. A cluster of intersecting conjugate faults at about 26 mbGL is associated with a large sub-karstic void as recorded in the calliper log and a similar slightly smaller feature is seen at about 32 mbGL. The feature on the calliper log at 41 mbGL is associated with an enlarged bedding parallel fracture.

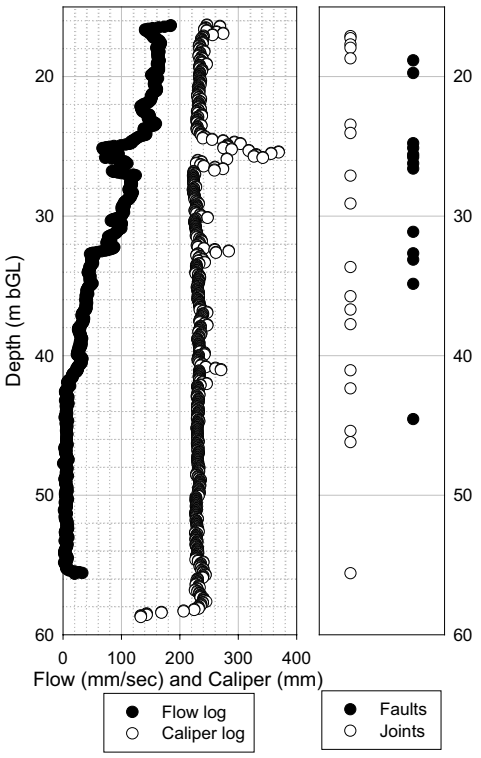

Figure 1. Typical flow and calliper logs and fracture logs derived from optical imager logs for a borehole at Frilsham Meadow

The flow log in Fig.1 shows the deepest significant inflow into the borehole is associated with the bedding parallel fracture at about 41 mbGL. There is then a continuous gradual accumulation of flow into the borehole above this depth. This trend is only disrupted by a small discrete inflow associated with the faults at about 32 mbGL and an apparent outflow associated with the sub-karstic void on the fault planes at 26 mbGL.

Borehole dilution tests at Trumpletts Farm are summarised graphically in Fig.2. Above about 50 mbGL inflow into the borehole causes a rapid dilution of the tracer over 200 minutes. There is only limited dilution in the depth interval 50 to 75 mbGL, although below about 85 mbGL there appears to be some flow into the borehole. The identification of a relatively active upper flow horizon down to 50 mbGL is consistent with the temperature profile at the site.

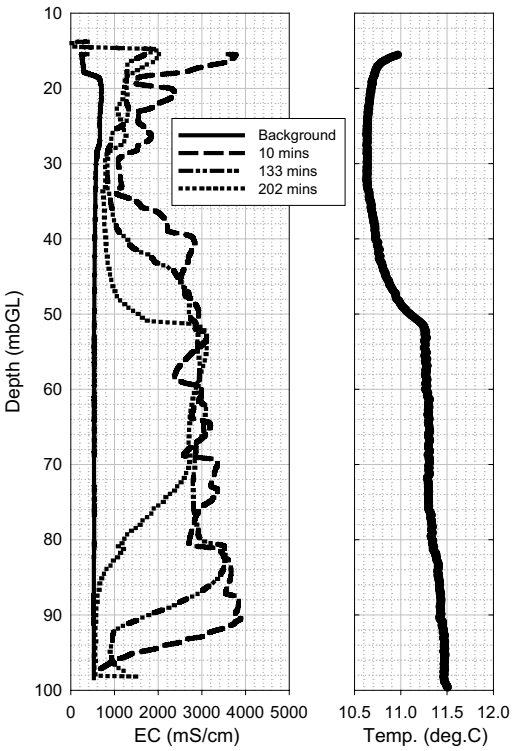

Figure 2. Graphical summary of the natural gradient borehole dilution test for the borehole at Trumpletts Farm

DISCUSSION

Even though the two sites are in contrasting locations, on an interfluve and in an area of groundwater discharge, the following common features can be identified: i) an active flow system in the upper part of the aquifer down to about 50 mbGL, and ii) an interval below about 50 mbGL where there is more limited flow into the boreholes. It is inferred that although large sub-karstic voids are present at both sites, much of the inflow into the boreholes is associated with flow along more minor, relatively undeveloped, joints sub-parallel to bedding. The results of packer tests at the Trumpletts Farm site suggest that there is a non-linear decrease in hydraulic conductivity with depth in the interval 40 to 80 mbGL, consistent with a reduction in fracture frequency with depth. Based on this observation and given the heterogeneity of flow into the borehole in this interval, as indicated by the borehole dilution test (Fig.2), it is inferred that flow into the borehole at Trumpletts Farm is affected by vertical variations in the head gradient in the immediate vicinity of the borehole.

REFERENCES

Allen DJ, Brewerton LJ, Coleby LM, Gibbs BR, Lewis MA, MacDonald AM, Wagstaff SJ, Williams AT (1997) The physical properties of major aquifers in England and Wales. British Geological Survey Technical Report WD/97/34

Bloomfield JP (1996) Characterisation of hydrogeologically significant fracture distributions in the Chalk: an example from the Upper Chalk of southern England. Journal of Hydrology 186:55-379

Price M (1987) Fluid flow in the Chalk of England. In: Goff JC, Williams BPJ (eds). Fluid flow in sedimentary basins and aquifers, Special Publication of the Geological Society of London 34:141-156

van Leeuwen M, de Stroet CBM, Butler AP, Tompkins JA (1998) Stochastic determination of well capture zones. Water Resources Research 342215-2223

Groundwater from crystalline bedrock in municipal of Leppävirta in southeast Finland

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A b s t r a c t : Potential fracture zone aquifers were traced in the area of municipality of Leppävirta in southeast Finland. The crystalline bedrock of the study area (50 km^2) comprises mainly Archean and Svekofennian schists and Paleoproterotsoic granitoids. Fracture zones were located from the topographic maps (DEM), the airborne geophysical data and refraction seismic soundings. As a result 8 wells are in production yielding 1 500 m^3/d in total. To analyse the research data discharge (q) values were calculated and seismic velocities of the bedrock were compared with the yield of the wells.

INTRODUCTION

The research area is situated in the municipality of Leppävirta in southeast Finland. Half of the 11,000 inhabitants live in two villages, which are situated about 10 kilometres from each other. The water consumption of the two population centres is about 1 200 m^3/d. The water supply was based mainly on surface water until 1990's when the cost-benefits and reduced health risks of groundwater based water supply became evident. Before the bedrock groundwater project, prospects for finding groundwater from glaciofluvial formations were investigated. The bedrock groundwater project started in 1991 and after different phases ended in 2000. In this paper the methods and hydrogeological issues of the project are discussed. The chemical issues of the Leppävirta case are presented in another paper presented at this conference (Klockars *et al.* 2003).

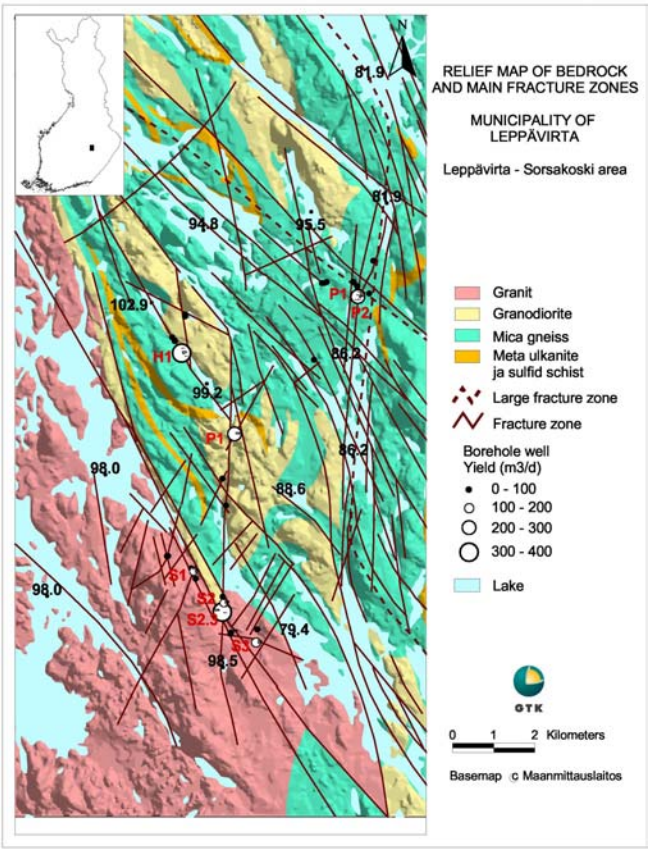

Figure 1. Main fracture zones and bedrock relief map of the study area

GEOLOGY

The bedrock of the study area (50 km^2) comprises mainly Archean and Svekofennian schists (1900 Ma) to the north and east, and Paleoproterotsoic granitoids (1900 – 1800 Ma) to the west and south (Korsman *et al.* 1997). The main rock types are mica gneiss and schists, granite, granodiorite, intermediate to mafic metavulkanites (Fig.1). The bedrock is covered by Quaternary deposits mainly till. Although the main aquifers in Finland are glaciofluvial formations deposited during the last deglaciation (10 000 BP), in the Leppävirta these formations are small and unsuitable for groundwater supply.

METHODS

First, potential areas for groundwater production were delineated based on a topographic map (DEM) analysis and interpretation. Subsequently, potential fracture zones were traced mainly from the airborne geophysical data. Also sulphide bearing schists and metavulkanites were located to avoid water quality problems. Also soil type and soil thickness were investigated. To locate fracture zones accurately, several seismic sounding lines were situated across the interpreted fracture zones. Refraction seismic soundings were the main method in selection of drill sites. Mapping of the structure of the bedrock on bedrock outcrops near seismic sounding lines was the final stage to select the point for the drilled wells (Tikkanen *et al*. 1994).

Altogether, 18 wells were drilled, ranging 160 - 270 mm in diameter and 50 – 115 meter in depth. The observations of the structure of the bedrock, yield and rock type were made from drilling cuts. Pumping tests were made in 13 wells. The yield varied between 45 – 400 m^3/d. Currently, 8 wells are in production yielding 1 500 m^3/d in total. At Leppävirta case the economic yield of the production well is 100 m^3/d.

After main phases of the project also gravimetric and magnetic field mapping were made to production well areas to analyse the variety of the fracture zone systems near Sorsakoski village.

DISCUSSION

Presently, production wells are situated in all main rock types. However, the contacts of different rock types appear to be particularly productive. In granite area at western part of the study area, several production wells tap the same fracture-zone system. Same fracture zones were found to be strongly weathered in a near-by-area where sand and fine sand sized gouge released into the wells damaged the pumps in short time. The production wells are located in fracture zones, which directions are N-S and SE-NW and dip are nearly vertical.

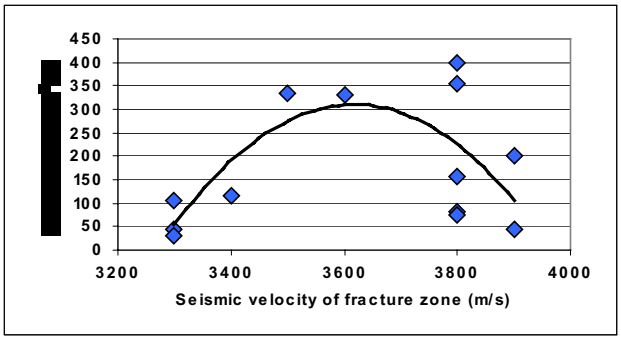

Figure 2. Seismic velocity of fracture zones compared to the pumping rate of bedrock wells in crystalline bedrock area in Leppävirta area in mid Finland

In the northern part of the study area hydraulic parameters calculated and hydraulic connection of the fracture zones were determined by analytic modelling (Leveinen *et al.* 1998). Based on pumping rates of test pumping of wells (Q) and the fracture zone cross section dimensions (A) the specific discharge (q) were calculated to be between 10^{-7} – 10^{-5} (1). Pumping rate (Q) is divided by 2 because of linear flow to well from opposite directions.

$$q = (Q/2)/A \text{ [m/s]} \qquad (1)$$

At Pohjukansalo site P1 and P2 in fig.2 the specific discharge and hydraulic conductivity noticed to be approximately same as the hydraulic conductivity 10^{-6} m/s in granite gneiss area based on modelling by Leveinen (1998) (Tab.1). The analysis between yield of the bedrock wells and the seismic velocity of the fracture zone systems showed, that the seismic velocity is 3 500 – 3 800 m/s in fracture zone of best pumping rate (Fig.2). The pumping rate noticed to depend also from the seismic velocity of the adjacent rocks.

CONCLUSIONS

The investigations of yield of drilled wells, seismic velocity of fractured bedrock as well as the structures and dimensions of fracture zones in Leppävirta have made possible to developed groundwater exploration procedures applicable in similar hard-rock areas lacking soil aquifers. Project has provided also an example for co-operation project between GTK, regional environmental authorities and municipalities. The specific discharge (q) is a possible method to asses of variations of the hydraulic conductivity (k) in fracture zone systems.

In future larger project is starting to the regional assessment of the fracture zones aquifers in crystalline bedrock areas. The main methods in this project are bedrock stress modelling (Holyland *et al.* 1997) and the analysis of the bedrock structure development history (Pajunen *et al*. 2002). Also new geophysical methods are examined to help on interpretation of bedrock aquifers. The aim of these projects is to get better regional predictions of the yield of the fracture zone aquifers in crystalline bedrock areas.

ACKNOWLEDGEMENTS

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REFERENCES

Holyland PW, Ojala VJ (1997) Computer-aided structural targeting in mineral exploration: two- and three-dimensional stress mapping. Australian Journal of Earth Sciences 44(4):421-432

Klockars J, Lipponen A, Breilin O, Kesola R (2003) Quality of bedrock groundwater in the communal supply wells of Leppävirta, eastern Finland. Extended abstract. Groundwater in fractured rocks. IAH conference in Prague 2003

Korsman K, Koistinen T, Kohonen J, Wennerström M, Ekdahl E, Honkamo M, Idman H, Pekkala Y (eds) (1997) Suomen kallioperäkartta = Berggrundskarta över Finland = Bedrock map of Finland 1:1 000 000. Geological Survey of Finland

Leveinen J, Rönkä E, Tikkanen J, Karro, E (1998) Fractional flow dimensions and hydraulic properties of a fracture-zone aquifer, Leppävirta, Finland. Hydrogeology Journal 6(3):327-340

Pajunen M, Elminen T, Mertanen S, Airo M-L, Wennerström M (2002) The polyphase Porkkala-Mäntsälä shear zone in southern Finland. In: Transport and flow processes in shear zones, 2-3 September, 2002, London: programme and abstracts. London: Geological Society 66

Tikkanen J, Forss H, Kesola R (1994) Bedrock groundwater - an unexploited groundwater resource in Finland. In: Suokko T, Soveri J (eds), Future groundwater resources at risk: poster papers of the international conference, Helsinki, Finland, 13-16 June 1994. Suomen Akatemian julkaisuja 4/94:285-291

Table 1. Geophysical and hydrogeological properties of fracture zones in crystalline bedrock area in Leppävirta in southeast Finland

Pumping site	Rock type	Seismic: Velocity (m/s)			Breadth of the fracture zone (m)	Open hole lenght (m)	Pumping rate (m^3/d)		Specific Discharge q = (Q/2)/A (m/s)
		Fracture zone	Adjacent bedrock A	Adjacent bedrock B			Test pumping	Production 2002	
Heinämäki H1	Mica gneiss	3800	4500	4500	15	50	400	380	$10^{-5,1}$
Pohjukansalo P1	Mica gneiss	3800	5000	5000	38	26	355	140	$10^{-5,7}$
Pohjukansalo P2	Mica gneiss	3500	4800	5000	25	55,2	335	140	$10^{-5,9}$
Haukilahti S2.3	Granite	3600	4900	5000	26	46	330	300	$10^{-5,8}$
Porttila P1	Granodiorite	3900	4300	5700	15	66	200	200	$10^{-5,9}$
Haukiniemi S3	Granite	3800	5400	5400	19	40	157	120	$10^{-5,9}$
Hiekkaharju S1	Granite	3400	5100	5100	20	87	117	100	$10^{-6,4}$
Haukilahti S2	Granite	3300	5100	5600	35	36	106	100	$10^{-6,3}$
Heinämäki H3.2	Mica gneiss	3800	5100	5600	67	49	81	-	$10^{-6,9}$
Heinämäki H3	Mica gneiss	3800	5100	5600	67	45	74	-	$10^{-6,9}$
Porttila P2	Granodiorite	3900	4300	5700	20	64,5	45	-	$10^{-6,7}$
Konninmäki K1	Mica gneiss	3300	5300	5300	25	40	45	-	$10^{-6,6}$
Hiirilampi HL2	Granodiorite	3300	5300	5100	14	43	30	-	$10^{-6,5}$

Geotectonics and groundwater in Precambrian rocks: the experience of the semi-arid Northeast Brazil

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A b s t r a c t : This paper discusses at first the influence of three major groups of variables on the quantitative and qualitative characteristics of groundwater in Precambrian rocks of the eastern Brazilian Shield, a semiarid region. These variables are from grounds of geotectonics, climatic and physiographic conditions and from general well characteristics, such as construction and maintenance. Secondly, regarding the basic fundaments of geotectonic regionalisation, it will be proposed a great diversity of the aquifer systems, as whole, from a tectonic domain to another, as well as it will be recognised seven major types of crystalline aquifer systems. Such classification is the achievement of 40 years of systematic observations in this eastern part of the Brazilian Shield, but it has to be still seen as experimental in character because a further revision is expectable. A complement of this proposal is to call the attention for geotectonic studies as support for groundwater research.

GENERAL OBSERVATIONS

Groundwater in fractured rocks plays a important role as strategic mineral resource for the eastern structural provinces of the Brazilian Shield (São Francisco Craton, to the south and the Neoproterozoic Borborema Province, to the north), most of which with their areas under semiarid climatic conditions.

About 100,000 water wells have been drilled in different parts of this region - of about 1,000,000 Km^2 - in the last two centuries. Only in the last 40 years technical criteria based on structural geology grounds started to be introduced, with very encouraging results. A substantial progress was accomplished in terms of location of water wells, and the amount of dry or/and abandoned water wells have since then decreased.

For aquifer systems of igneous and metamorphic rocks, a context of great diversity of problems has been recognised. The general simplism of many textbooks and papers cannot be acceptable anymore. There are aquifer systems and aquifer systems, ad this evoked paraphrase from Read is valid. Such diversity is determined by three different major groups of variables from the domains of Geotectonics, climatic conditions + physiography and from the overall water well characteristics/ conditions (tab.1, next page).

The understanding about the extraordinary diversity of the crystalline aquifer systems was gradually achieved, with the practice of attending water supply needs of different (geographic and geotectonic) regions of the eastern Brazilian shield. For each crustal type, the general conditions of the aquifer systems have showed substantial differences (and peculiarities). For some microclimatic domains with either higher or regular annual rainfall rates, some minor dependence of the lithological and structural associations has been verified.

This paper postulates that, if it will be possible to maximise the third group of factors of the tab.1 (well design, well construction etc.), for a same area, the knowledge of variables of the tectonic point of view would be of outstanding importance. In sum, it is possible to use the knowledge of the tectonic regionalisation to improve the choice of the best water well sites (always and everywhere).

The São Francisco structural province is a syn-Brasiliano cratonic nucleus, with a basement composed mostly of high grade terranes (some minor greenstone belts) and fold belts and covers of Paleoproterozoic and Mesoproterozoic ages, as well as a extensive pelitic-carbonatic cover sequence of Neoproterozoic age. The Borborema structural province is a complex branching system of orogens (marginal and distal belts) of Neoproterozoic development, with frequent exposures (several types of basement inliers) of the Paleoproterozoic basement.

MAIN AQUIFER SYSTEMS

The tectonic and hydrogeological observations carried out in the last 40 years are suggesting the (experimental) discrimination of at least 7 different types of crystalline aquifer systems, as pointed out in tab.2, next page. The informal discrimination in capital letters is trying to follow the natural order of importance (rank), but this is not an essential premise. Some transitional features could be observed from a proposed aquifer system to another (e.g. A-B; C-D, etc.). Additionally, some subdivisions of these main types are possible to be done, but this should wait to be subject of further analyses.

It is necessary to add and remark that the quantitative and qualitative data of all aquifer systems will be substantially improved when they will be occurring in humid areas (coastal areas, microclimatic oasis). Nevertheless the validity of the tectonic factors (item 1, tab.1) will still remain manifest.

A-type aquifer systems uses to present shallow water table, and locally artesian conditions may be developed. The greatest water well yield known in Northeast is from this type of aquifer system. In B-type, Q/s uses to increase with karst dissolution and the intensity of folding (and related fractures). The same is true for C and D-types, and in these particular cases local fault zones have been rather important. Several transitional conditions may be detected in the field from A-type and B-type, and B-type (flat - lying rock units) to C and D-types (folded rock units).

Usually, E-type and F-type assemble the worse general conditions for groundwater research and exploration. Some local lithological - quartzites, meta-arkoses, quartzitic ranges (E', F'), granitic ranges (E", F"), structural (fault zones) and orographic (greater rainfall rates, vadose waters) features may minimise those very difficult general conditions. In some of these cases (springs, vadose waters) other types of catchment are advisable (rather than water wells).

Long and linear polycyclic shear zones are a remarkable features of that part of the Brazilian Shield. But, for this so-called G-types aquifer systems, there is not, up to now, enough critical mass of data to define quantitative and qualitative results. There are some important zones for exploration where there was the overprint of modern (Meso-Cenozoic) fields of extensional tectonics.

Table 1. Main group of variables for the crystalline aquifer systems

1- Geotectonics: (internal dynamics)	Paleotectonics	Crustal type Rock assemblages and their stratigraphic relationships Structural associations
	Neotectonics	Overprint of Cenozoic structural stress fields (veneers of) Modern sedimentary deposits
2- Clima and physiography (external dynamics)		Annual rainfall rates and distribution versus Evapotranspiration rates Recharge availability
3- General characteristics of the water well (men's interventions)		Selection of well site and location (hydraulic conductivity obtained) Well design, construction and development Maintenance and usage

Table 2. Main Aquifer Systems and their hydrogeological characteristics - Northeast Brazil

Aquifer System	Litho-structural components	Noteworthy features	Specific Capacity (Q/s) m^3 /h m	Water Quality TSD : mg/L
Paleoz. and Meso -Proterozoic cover (A)	QP > C assemblages: Quartzite-metapelite-carbonate	Porosity of interstices, fractures, stratigraphic joints, contacts, unconformities	0.5 - 1.0 ⇒ 25.0	0 - 600
Neoproterozoic Covers (B)	C > QP assemblages: Carbonate, meta-pelite, quartzite	Porosity of fractures and karst dissolution. Local slaty cleavage	0.5 - 0.8 ⇒ 4.0 – 6.0	500-1,000 1,000-2,000
Thrust-and-fold belts and Marginal belts (C and D)	QPC assemblages + Meta-diamictites and meta-turbidites	As above Metacarbonates and slaty cleavage very important.	0.5 - 2.0 ⇒15.0–350.0	500-2,000
Interior (distal) Fold Belts E (E', E")	Schists, meta-arkoses, meta-volcanics (bimodal): BVAC assemblage + QPC assemblage	High granitic and quartzitic ranges are important (E'and E"), as well as quartzites and carbonates	0.1 - 0.2 ⇒ 1.5	2,000-5,000 ⇒20,000
Basement of cratons, "massifs" (inliers) and fold belts F (F', F")	High grade terranes : orthogneisses, migmatites. Minor supracrustals	Granitic and quartzitic ranges may be important (F', F").	0.1 - 0.2 ⇒ 1.5	>2,000 ⇒10,000
Shear Zones / Lineaments G	Cataclastic rocks s. l. up to 20 km wide. Polycyclical behavior	"T" fractures are important. Overprint of modern tensional stress fields	- - - - - - - -	- - - - - - - -

Observ: ⇒ Maximum (noticeable) values; Q = quartzites; P = pelites; C = Carbonates; BVAC = Bi – modal volcanics, arkose, conglomerates.

The conceptual model of two "potenciometric surfaces" in fractured rock aquifers overlain by thick soil coverage

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A b s t r a c t : The so-called "two potenciometric surfaces model" show the relation of two different aquifers in terms of porosity and general water circulation conditions. The model shows that two unsaturated zones can be identified, related to the shallow porous system, and the deep fractured aquifer. Due to capillary forces a hydraulic barrier is developed in the limit of the base of the soil/saprolite aquifer and the fractured/fissured aquifer. The leakage of water from the top to the bottom is just possible when the hydraulic head in the shallow domain reaches a certain level to break the barrier. The hydraulic barrier is related to fine sediment deposition, capillary forces and the quick contrast of porosity. The proposed model can be applied to the high plateaus of the Braziian savanna region and is important to the groundwater management and development.

INTRODUCTION

In the plateaus of the Brazilian savanna a phenomena can be observed. Two unconfined aquifers exist in areas where the soil and the weathered zone are building up thick layers of some tens of meters over fractured quartzite rocks. The upper aquifer can be observed in the porous media and the second aquifer in the fractured rocks. The aim of this abstract is to show the relation of groundwater in both media.

The "two potenciometric surfaces model" states that there is an unsaturated zone between the base of the saturated zone of the upper aquifer and the saturated zone of the fractured rocks (fig.1).

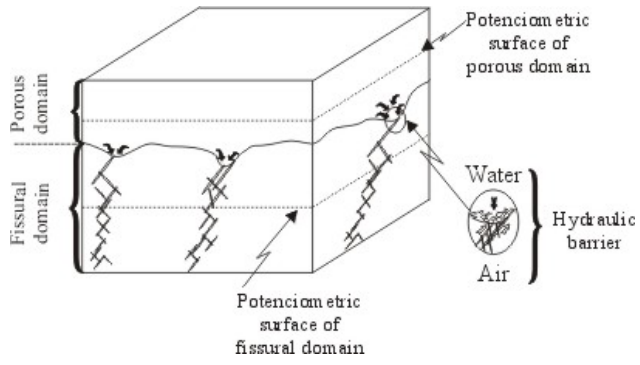

Figure 1. Model of two potenciometric surfaces (from Campos and Freitas-Silva 1998)

Both groundwater bodies are not separated all time long. They can be observed isolated from one each other during the dry period while drilling a well. The bottom of the top aquifer is in conformity with the top of the solid quartzite rock. The marked fractures in the rock are opened wide in this interface between weathered zone and solid media. For some meters they are dry and groundwater can only be detected after a certain depth (typically from 50 to 75 meters in the case studies).

In the interface of the water bodies there is a hydraulic barrier that does not allow the free water flux from continuos leakage. The barrier is controlled by the presence of weathered material, which consists of fine sediments in silt to clay fraction. These sediments have the function of a capillary barrier.

During the recharge of the porous upper aquifer a reaction of leakage can be observed after a significant rise of the groundwater table. Even than an interface of a remarkable thickness remains and only in some cases a unifying of the both aquifers can be observed. Under these circumstances still two hydraulic heads can be measured. Also the chemistry of the shallow and the deep groundwater is different. This indicates that the recharge of the fractured hard rock aquifer takes only place to a certain amount.

DISCUSSION

This model is based on empirical observations in the aquifers of the Federal District area and the neighbourhood, during the construction of deep wells, the monitoring of springs discharge, the evaluation of watershed behaviour and the monitoring of water level in the different aquifers. The general hydrogeology of the region is available in Campos and Tröger (2000).

The main arguments that support the proposed model are present and discussed as follows:

1 – During the drilling of wells it is common to have water loss when the first fractures are intercepted. In general the water is stored in the soil/saprolite aquifer. When the drilling gets to the unsaturated fractures the water from shallow aquifer migrates fast and disappears in the open fractures. Bellow 50 to 75 meters all fractures that are intercepted result in the increase of the water well discharge. This phenomenon was observed during some well construction, where a fast pumping test was carried out after each 10 meters of perforation.

2 – Some water wells that have the shallow portion totally isolated show a lower piezometric head for the fractured zone in comparison with the piezometric head of the vadose zone of the porous aquifer.

3 – The exploitation of water by shallow wells in the porous aquifers do not interfere by the pumping of the deep wells even in the sites where a high density of deep wells is observed. It shows there is not a direct relation between these aquifers systems.

4 – The presence of vadose caverns where many shallow wells explore water from the porous aquifer. The unsaturated caverns are related to lenses of marble and are observed from 36 to 70 meters. The deep tubular wells just pump waters when the saturated caverns are intercepted. Despite these wells explore tens of cubic meters per hour, there is no interference of the shallow wells water levels that varies from 8 to 19 meters depth.

5 – The discharge of natural springs confirms the proposed model. Cadamuro (2002) evaluated two sets of springs in a high plateau of the Federal District region and showed that there is an important difference in the behaviour of the springs discharge. The springs situated in the porous aquifers show an increase of discharge one month after the recession precipitation period. By the other hand, the springs situated in rock outcrops (related to the fractured aquifers) just begin the increasing of discharge two to three months after the beginning of the rainy period. This behaviour suggests that the recharge of the fractured domain aquifer takes longer because of the later starting discharge of the upper porous aquifer.

6 - Another argument was studied by Souza (2001) on the monitoring of a little watershed in the Federal District region. The measure points were distributed in thick soil areas and in the rock outcrops portion of the basin. In the porous aquifer (soil region) the base flow show an incremental factor proportional to the increment of the area. The observation in the fractured aquifer shows in some cases a decrease of water discharge or an insignificant increase. This study confirms the importance of the shallow aquifers base flow for the permanent flow of the streams. Despite to the three/four months period of rain recession the majority of the streams are perennial. This study also corroborates the "two potenciometric surfaces model".

7 – At the border of the plateaus region the groundwater behaves different. In these areas where the soil coverage is thin (less than 2 meters), there is just one unsaturated zone above the saturated fractures. A second upper aquifer can not be observed. This observation demonstrates that the model is just valid to the interior of the plateaus.

The deeper potenciometric surface is not really a regular surface, like the ones observed in isotropic and homogeneous aquifer. The fractures are not linked to on each other. That is why in this case the so-called potenciometric surface is the mean water table in the fractured rock. The monitoring of the water levels shows that the top of the saturated zone in the hard rock domain is irregular and is defined by different blocks limited by the regional faults/fractures zones. The top of the saturated fractures is also not horizontal, and must be seen as a tabular surface inclined towards the main conductive fracture zones.

IMPLICATIONS

The knowledge of a conceptual model is important to deal with groundwater recharge and abstraction. In the case of aquifers developed in fractured hard rock this kind of model must help to understand some phenomena observed in some systems. It is also important for all kind of management including circulation conditions, deep well screening and construction, projects on artificial groundwater recharge, protection of the aquifers and definition of the sustainability of exploration. Some distortions on mathematical models applied to some fractured aquifers can be explained by this model.

It is important to point out that the purposed model is not valid to any system that shows thick regolith over igneous or metamorphic rocks, but just for the cases where the relief pattern is characterised by plateau areas with thick soil and weathered zone on the top of fractured rocks.

The plateau areas do not allow the development of local or intermediate flow pattern, and as it is shallow and not thick is does not allow the regional flow to the discharge of the aquifers. So the relation of the porous and fractured aquifers is a kind of natural equilibrium between the two groundwater systems.

CONCLUSIONS

The described model exists in the high plain relief of the Federal District where the thick sandy/clayey soil overlays quartzites and sandy metarrithmites fractured sequences. The fracture pattern is of high density and very well interconnected, but is of low aperture (0,1 to 5 mm opening). This situation contrasts with the homogeneous intergranular porosity of the soil/saprolite coverage and results in the formation of a hydraulic barrier in this contact.

Studies based on isotopic data, detailed hydrochemistry and piezometric levels monitoring must be done to confirm this empirical model.

The proposed model is not valid to similar systems where the mean fracture aperture is smaller, getting to the scale of the capillarity of the porous media. In these cases only one aquifer is to be expected.

REFERENCES

Cadamuro AL, Campos JEG, Tröger U (2002) Artificial recharge in fractured rocks – an example from the Federal District of Brazil for the sustainability of the system. In: Dillon P (ed.), Management of Aquifer Recharge for Sustainability, Proc. of 4th International Symposium on Aquifer Recharge, Balkena, p. 523-526

Campos JEG, Freitas-Silva FH (1998) Inventário hidrogeológico e dos recursos hídricos superficiais do Distrito Federal. Brasília, IEMA/SEMATEC/UnB. p.1-87. (Vol. IV Relatório Técnico)

Campos JEG, Tröger U (2000) Groundwater Occurrence in Hard Rocks in the Federal District of Brasilia. A Sustainable Supply?. In: Sililo, Groundwater: Past Achievements and Future Challenges, Proc. of XXX I.A.H. Congress. Cape Town, South Africa, Balkena,p. 109-113

Souza MT (2001) Fundamentos para gestão dos recursos hídricos do Distrito Federal. Instituto de Geociências, Universidade de Brasília, Brasília, MsC. Dissertation, 94 p

Hydrogeological characterisation of low-permeability rocks in the north Africa (Ceuta, Spain)

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A b s t r a c t : The hydrodynamic characteristics (pumping outflow, specific outflow and transmisivity) of low permeability materials in the North of Africa (Ceuta, Spain) have been achieved by way of hydraulic and recovery testing in boreholes and piezometers.

The town of Ceuta is situated in the north of Africa and has a population of 80,000 inhabitants. Its water resources are supplied by two dams with a whole capacity of 2.5 hm^3, several drillings and some springs situated far from the city. However, the available total resources are not enough to cover all the water demand.

The study area is placed in the northern part of the Rift range, which forms part of the Gibraltar Arc structure. This structure is the connection between the lithostratigraphic units of the South of Andalusia (Spain) and the North of Morocco (Didón *et al*. 1973).

The area belongs to the Internal Zone of the Rift chain as well as Septides and Ghomarides units (Serv. Geol. de Maroc 1979) and they are the objectives of this research. Those units are equivalents to the Alpujarride and Malaguide complexes of the Betic range.

The annual average rainfall on this area is 850 mm.

From a hydrogeological point of view (fig.1), two groups can be distinguished:

(1) High permeability rocks, represented by *alluvial deposits*, of limited thickness and with scarce outcrops, in which some wells for water supply occur; and *limestones and dolomites* (Triassic) of a high transmisivity, although they present scarce water resources again due to limited extension of their outcrops, and

(2) low permeability rocks, represented by *gneisses, schists*, *phyllites* with quartzite intercalations, *slates* and *psammites*, *carbonated slates* of Palaeozoic age, *clays and sandstones* of Permian-Triassic age, with scarce hydrogeologic importance due to the cementation grade and a low surface, and finally, *clays* and *sandstones* (Flysch) of Eocene age.

To reveal the new water sources, hydrogeological research was carried out. In its frame 37 drillings (25 wells and 12 boreholes) of a total drilling depth of 2081 meters have been carried out. Almost all were situated in low permeability rocks (gneisses, schists, slates, psammites and carbonated slates). This drilling phase has permitted to know their hydrogeological characteristics as well as the water volume that can be pumped (CHS 1995).

The depth of wells ranges between 50 and 140 m but the majority of them (29) are of 50 m deep. All wells were carried out by the rotary-percussion method coupled to a pneumatic hammer. Pumping wells were drilled with a diameter of 320 mm in their upper parts and 220 mm till the end of the borehole. In the upper part the steel casing of 300 mm diameter was installed. Furthermore, all the wells were installed with a PVC casing of 250 mm. Slotted casing was placed in the most permeable sections of boreholes. Piezometers were drilled with a diameter of 180 mm and installed with PVC 75 mm of slotted casing.

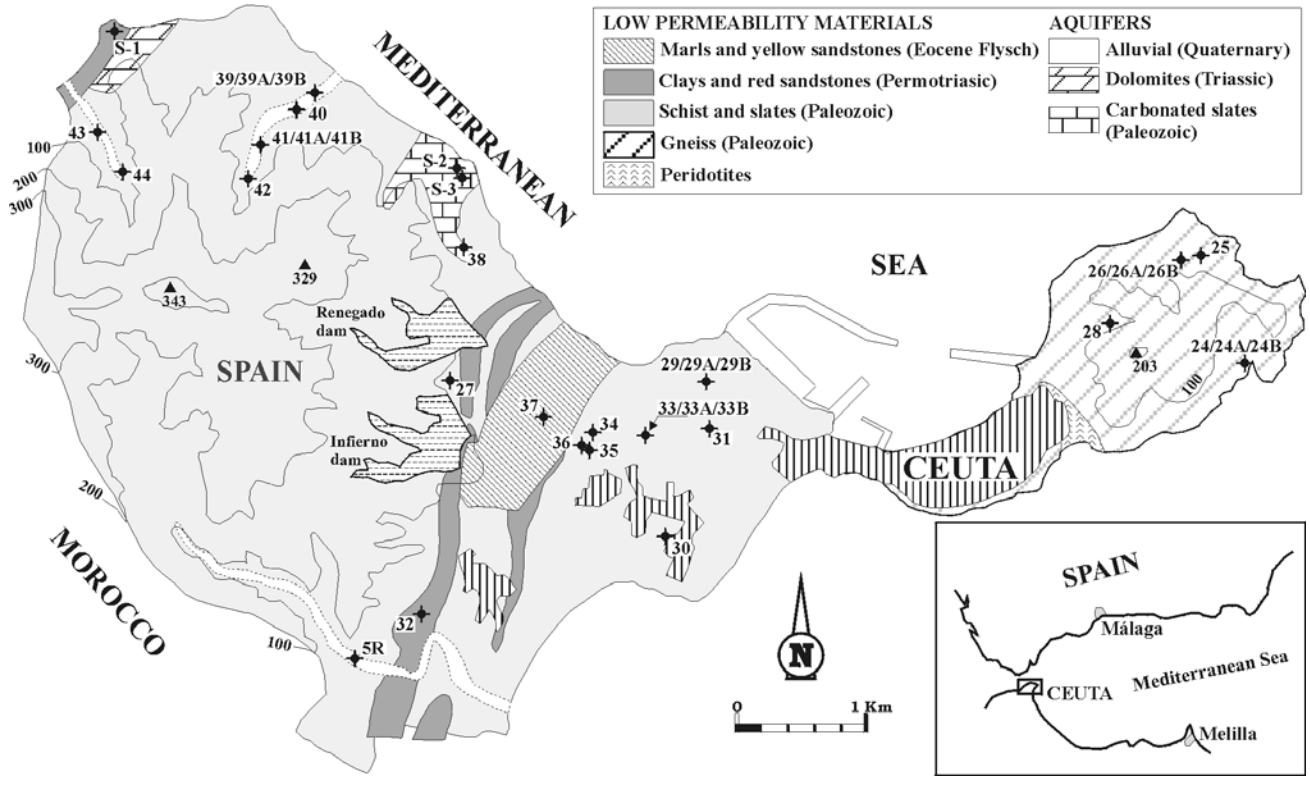

Figure 1. Hydrogeological framework of the study area

The distribution of the wells related to the different lithology is as follows: schists, 16; gneisses, 4; carbonated slates, 2; red sandstones and clays, 2 and clays and sandstones (Flysch), 1.

Gneisses outcrop in the eastern part of the city, constituting a small peninsula. They are covered by a thick weathered layer up to 28 m, in which a scarce volume of water is stored.

Schists, phyllites, slates and psammites constitute the majority of the territory. They form a very thick unit with a weathering zone of less than some tens of meters. Rain water accumulates in the weathering zone, and in the joints and fractures of the rocks, commonly filled with clay. The quartzite intercalations are more permeable. The carbonated slates present slightly higher permeabilities although they provide low water volumes.

The red sandstones of Permotriassic age are of small hydrogeological importance due to their cementation and few outcrops in the area. Clays and sandstones (Flysch) due to their low permeabilities are also of a low hydrogeological importance.

In all cases the piezometric level is near the surface and always related to the weathering zone.

In 22 wells, pumping tests were done for periods of 24 hours with increasing outflow and a recovery time of 6 hours.

In fig.2 specific capacity (m^3/day m) with well yield (m^3/day) is correlated. Differences in hydrogeological characteristic can be observed. The carbonated slates indicate higher specific capacity (above 100 m^3/day m) - particular wells reach a yield up to 5 L/s.

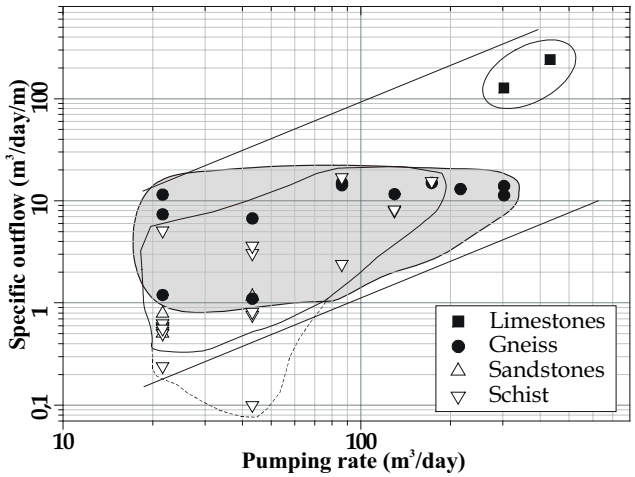

Figure 2. Specific capacity against the pumping rate in lower permeability rocks of Ceuta area

Gneisses have a lower specific capacity (between 1 and 15 m^3/day m) with an average value of 9 m^3/day m, with yields between 0.5 and 3.5 L/s.

The schists can be divided into two groups: most of wells proved a low specific capacity (0.6 m^3/day m) with a yield of 0.25 L/s. In some of the wells the pumping test had to be stopped when the drawdown reached the pumping device. In fractured schists or in their quartzite intercalations an increase in the specific capacity was observed (5-17 m^3/day m); the yield of wells ranged between 1 and 2 L/s.

The red sandstones of Permotriassic age did not differ in their values from the low permeable schists.

The determined transmisivities from the recovery tests (tab.1) correspond to the mentioned specific capacities. The highest transmisivities were assessed in carbonated slates (240 m^2/day). Values between 1 and 15 m^2/day were obtained in fractured gneisses and/or in quartzite schists. The lowest values, even less than 1 m^2/day, correspond to schists and red sandstones.

The groundwater is of a mixed type with the most frequent ions HCO_3^- and Cl^- and Ca^{2+} and Na^+. The maximum electrical conductivity was 1300 µS/cm, with higher values in the wells affected by waste contamination or by sea-water intrusion.

	Transmisivity (m^2/d)
Carbonated slates	240
Gneiss	0.5 - 24
Schist with quartzite and/or fissured	1-15
Schist	0.2 – 0.7
Red sandstones of Permian-Triassic age	0.2

Table 1. Transmisivity of the materials, according to the recovery tests

ACKNOWLEDGEMENTS

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REFERENCES

Didon J, Durand-Delgá M, Kornprobst J (1973) Homologies géologiques entre les deux rives du Détroit de Gibraltar. Bull Soc Géol de France XV:77-105

Service Geologique du Maroc (1979) Carte geologique de Sebta. Echelle 1:50.000. Ministere de l'energie et des Mines (Maroc)

Confederación Hidrográfica del Sur (1995) Obras de emergencia para aprovechamientos hidrogeológicos en Ceuta para mejorar el abastecimiento urbano, 209 pp

Comparing transmissivity classes of hard-rock aquifers in the Iberian Peninsula and the Bohemian Massif

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A b s t r a c t : Igneous, metamorphic and strongly cemented sedimentary rocks are widespread throughout extensive areas of Europe. Regionally prevailing transmissivity of hard-rock aquifers is compared in two extended domains differing in geomorphologic and climatic conditions, groundwater demand and water-supply conditions: in the Bohemian Massif (Central Europe) and in the two areas of the Iberian Peninsula. In addition to the dominant effect of rock fracturing that results in similar transmissivity classes everywhere, smaller differences seem to exist between particular petrologic types. In the Bohemian Massif higher values might be expected in areas built by basic igneous rocks and by some granites. In South Portugal gabbros, gneisses and migmatites seem to be more intensively fractured and weathered and, on the other hand, higher transmissivity has been indicated in some granitoid areas of the Central Spain.

INTRODUCTION

Igneous, metamorphic and strongly cemented sedimentary rocks are widespread throughout extensive areas of Europe (fig.1). Two of these domains correspond to the Bohemian Massif and the Iberian area, both including rocks strongly affected by Precambrian, Caledonian and Variscan orogenies. Based on available data from both areas a comparison of prevailing transmissivity was carried out.

AQUIFER CHARACTERISATION

In terms of hydrogeology, three distinct vertical zones can be distinguished in most of hard rocks. The uppermost weathered zone with dominant interstitial porosity, the intermediate zone characteristic mostly of a relatively dense fracturing, and the lower massive bedrock zone that is mostly characterised by a less frequent fracturing but sometimes with deep-seated fault zones enabling mineral and thermal water flow.

The upper and intermediate zones form the main regional "shallow" aquifer. The thickness and character of this aquifer varies according to faulting and fracturing, rock petrography, weathering, morphology and climate (Larsson *et al.* 1987).

Hard rocks of the Bohemian Massif are characterised by a wide variety of petrographic types: igneous rocks ranging from granite to basic rocks, and metamorphic rocks including various types of gneiss, migmatite, mica schist, phyllite, granulite, etc. Shale, greywacke, sandstone and conglomerate mainly represent sedimentary rocks.

In the Iberian Peninsula two areas were selected to be compared. In South Portugal, where scattered groundwater supply depends on hard-rock aquifers, igneous rocks are represented by granites, granodiorites, quartzodiorites, diorites, gabbros and porphyries. Schists, metamorphic greywackes and conglomerates, gneiss and metamorphic volcano-sedimentary complexes represent the main types of metamorphic rocks.

In the central part of the Iberian Peninsula, in Spain, the importance of hard-rock aquifers is relative, due to the presence of important sedimentary basins. Therefore, only a few hydrogeologic studies were carried out, namely in the meridional slope of the Central System (Massifs of Somossierra, Guadarrama and the oriental sector of the Gredos Massif). López-Vera (1984), Yélamos (1991) and Martín-Loeches (1995) carried out the studies to assess groundwater abstraction possibilities. This area is represented by low-grade metamorphic rocks (schists, quartzites, slate-like schists), medium- and high-grade (schists, mica schists, gneisses) and granitoid rocks (adamellites, leukoadamellites, granodiorites).

In the Portuguese area the climate is semi-arid. The uppermost weathered zone is typically up to 2 - 6 meters thick (Chambel 1999) except for some igneous basic rocks, mainly gabbros (Duque 1997) or metamorphic gneisses and migmatites (Fialho *et al.* 1999) where the weathered/highly fractured zone can reach 20 to 40 m deep. In the central area of Spain the precipitation is higher and, in opposition to the Portuguese sector, which is mainly flat, the relief is mountainous.

In the Bohemian Massif area the climate is temperate and the uppermost weathered zone, together with juxtaposed Quaternary deposits is thick in valleys, resulting in a differences between the transmissivity in elevated areas and valleys, also due to differences in tectonic predisposition and hydrogeologic position (Krásný 1999). Possible differences in transmissivity of recharge /discharge areas have not yet been studied in the Iberian area.

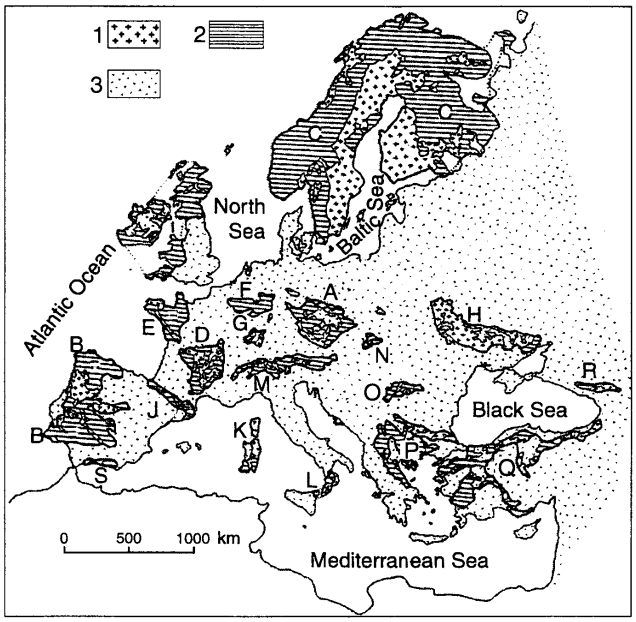

Figure 1. Main hard-rock occurrences in Europe (after Krásný 1999)

Dominant rock types: 1 - igneous, 2 - metamorphic and /or intensively folded sedimentary (mainly clastic), 3 - others.

Massifs and shields (A-H): A - Bohemian Massif, B - Iberian area, C - Nordic area (Baltic Shield), D - Massif Central, E - French Armoricain Massif, F - Ardenne-Rhine area, G - Vosges and Black Forest, H - Ukraine Shield, I - UK and Ireland.

Cores of Mesozoic and Cenozoic orogenic belts (J-S): J - Pyrenees, K - Corsica and Sardinia, L - Calabria and Sicily, M - Alps, N - West Carpathians, O - South Carpathians, P - South Balkan, Q - Anatolia, R - Caucasus, S - Betic zone.

COMPARISON OF HARD-ROCK TRANSMISSIVITY

Transmissivity is an important hydraulic property of aquifers. Therefore, knowledge of transmissivity distribution helps to draw important conclusions from hydrogeologic studies, providing a basis for future groundwater exploration, development, abstraction and protection (Krásný 1993).

In order to compare objectively transmissivity values on local and regional scales, including their representation in hydrogeologic maps, Krásný (1993) introduced a classification of transmissivity magnitude and variation. In addition to other parameters, expressing transmissivity, the index of transmissivity Y [a logarithmic transformation of specific capacity q - $Y=\log(10^6 q)$ where specific capacity q is expressed in L/s/m] can well be used in regional hydrogeologic studies.

The classification consists of six classes of *transmissivity magnitude* (I - very high, more than 1,000 m^2/d, to VI - imperceptible, less than 0.1 m^2/d) and of six classes of *transmissivity variation* (class a - insignificant variation, indicating almost homogeneous hydrogeologic environment, with standard deviation of the transmissivity index Y less than 0.2, to class f - extremely large transmissivity variation, i.e. extremely heterogeneous hydrogeologic environment - standard deviation of the index Y more than 1.0). In this way transmissivity data can be compared in different areas.

Based on results of hundreds of pumping tests carried out in drilled and dug wells in the Czech part of the Bohemian Massif Krásný (1999) concluded that, in the Bohemian Massif, the regionally prevailing transmissivity of hard rocks ranges commonly between classes V to III (0.1-100 m^2/d), the most frequent being the class IV(-III)c,d (units to slightly more than 10 m^2/d), i.e. low to intermediate transmissivity with moderate to large transmissivity variation. Transmissivity up to one order of magnitude higher is typical for crystalline limestones (marbles). There are also some indications that higher transmissivity might be expected in areas formed by basic igneous rocks and some types of granites. On the other hand, phyllites display a lower regional transmissivity in some areas. In general, however, essential differences caused by rock fracturing and weathering "mask" the smaller differences between distinct petrologic types. The same can be said about the rocks in the Iberian area.

In the southern part of Portugal, an inventory of more than 7,000 water points in hard-rock aquifers was carried out during the recent studies. About 2,000 of them have a hydraulic information on air-lift tests when compressed air is conveyed to the bottom of wells. These data are not adequate to determine exact hydraulic characteristics but might be used in statistical treatment of regional (comparative) parameters. Due to some uncertainties regarding water levels and resulting yields and drawdowns simplifying premises have to be accepted as discussed by Mira and Chambel (2001). Based on these assumptions the results would maintain quite conservative.

In Southwest Iberia the results indicate that transmissivity of schists and granitic rocks (granites, granodiorites, quartzodiorites, etc.) belongs to classes IV(-V)c, with values mostly between 0.55-4.49 m^2/d in schists and greywackes and 0.51-6.95 m^2/d in granitoids. Moderate transmissivity variation prevails everywhere. The porphyries belong to class IV(-III)d, with transmissivity values between 1.16-19.22 m^2/d and a large variation. The basic igneous-rock aquifers, mainly gabbros and charnoquites, and the metamorphic-rock aquifers, like gneisses and volcano-sedimentary rocks, belong to classes IV-IIIc,d or IV b. Particular rock types might be characterised by values of prevailing transmissivity ranging between 1.42 and 21.38 m^2/d (with moderate variation - class c) - gabbros, 1.29 and 30.55 m^2/d (with large transmissivity variation - class d) - gneisses. On the other hand, both volcano-sedimentary rocks with prevailing transmissivity between 1.61-9.48 m^2/d and charnoquites (1.12-5.7 m^2/d) appear to have small transmissivity variation (class b).

In Spain, in spite of some limitations as to the availability and reliability of data, it is possible to assess tentatively the following transmissivity classes: slates (T<0.1 m^2/day, class VI); schists (10>T>1 m^2/day, class IV); micaschists and schists (10>T>1 m^2/day, class IV); gneisses and schists (8>T>0.3 m^2/day, class IV and V); gneisses (10>T>0.3 m^2/day, class IV and V); adamellites, leucoadamellites and granodiorites (100>T>30 m^2/day, class III).

CONCLUDING REMARKS

Similar patterns were found in two different hard-rock regions of Europe: in the Bohemian Massif and the Iberian area. Particular transmissivity values determined by pumping tests mostly range between 0.1 and 100 m^2/d. Regionally prevailing transmissivity, however, can be typically expressed by classes IV-III c,d. In addition to crystalline limestones (marbles) with evidently higher transmissivity there are some indications that in both regions higher prevailing transmissivity might be found also in basic igneous rocks. Regarding other rock types, no general conlusions have been drawn. Yet, in some areas, some granitic rocks, gneisses and migmatites display higher values.

In both regions igneous rocks tend to have higher transmissivity values in shallow parts with quite abrupt permeability decrease with depth, while in metamorphic environment the depth-related decrease of permeability is slower. In the Bohemian Massif important differences were proved depending on geomorphologic and hydrogeologic position of rocks: prevailing transmissivity was assessed 2 to 4.5 times higher in discharge than in recharge zones. No studies of this kind have yet been carried out in the Iberian area.

REFERENCES

Chambel A (1999) Hydrogeology of Mértola region (in Portuguese). Doctoral Thesis, Univ of Évora, Évora, Portugal, 380 pp

Duque J (1997) Hydrogeological characterisation and mathematical modelling of the gabbros of Beja aquifer (in Portuguese). Master Thesis, University of Lisbon, Lisbon, Portugal, 220 pp

Fialho A, Chambel A, Duque J (1999) Relation between geomorphology, land use and water management in the Gneissic and Migmatitic Aquifer System of Évora (South Portugal). In: Fendeková M, Fendek M (eds) Proc. XXIX IAH Congress, Hydrogeology and Land Use Management, Bratislava, Slovak Rep, 159-163

Krásný J (1993) Classification of transmissivity magnitude and variation. Groundwater 31,2:230-236

Krásný J (1999) Hard-rock hydrogeology in the Czech Republic. Hydrogéologie, 2:25-38 Éditions BRGM. Orléans.

Larsson I *et al.* (1987) Les eaux souterraines des roches dures du socle. Etudes et rapports d'hydrologie 33 UNESCO, Paris, 280 pp.

López-Vera F (1984) The groundwater in Madrid Community (in Spanish). Monogr. PIAM nº 7. Com. de Madrid Madrid, Spain

Martín-Loeches M (1995) Hydrogeology of igneous and metamorphic rocks in a sector of the Alberche river basin and its relation to the groundwater of the Madrid area (in Spanish). Doct Thesis, Univ de Alcalá, Fac de Ciencias. Madrid, Spain

Mira F, Chambel A (2001) Productivity of hard-rock aquifers in the Alentejo region, South Portugal. In: Seiler & Wohnlich (eds) Proc XXXI IAH Congress: New Approaches Characterising Groundwater Flow, Balkema, Lisse (Holand), 2:1035-1039

Yélamos JG (1991) Hydrogeology of the plutonic and metamorphic rocks of the meridional slope of the Sierra de Guadarrama (in Spanish). Doct Thesis, Univ Autón de Madrid, Spain

Relationship between the permeability of hard-rock aquifers and their weathered cover based on geological and hydrogeological observations in South Korea

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A b s t r a c t : As part of a hydrogeological mapping project, a joint geological and hydrogeological study has been performed in the two hard-rock regions comprising granite, metasediments and gneiss in South Korea. Weathering in Korea deeply affected the hard rocks and resulted in a typical weathering profile. The statistical analysis of existing well yields reveals no evidence to suggest a relationship between well yield and tectonic fracturing. On the contrary, it appears that the weathered cover plays a determining role in terms of the transmissive properties of the hard rocks and not only in term of their water-retention capacity. The weathered-fissured horizon, generally attributed to decompression that develops within the uppermost tens of metres of the "fresh" basement substratum is clearly due to weathering processes. Thus, well yields are statistically much higher in regions where a weathered cover (alterites + fissured zone) is preserved than in places where these horizons have been eroded. Mapping the geometry of the different compartments making up the aquifer at catchment scale opens up major development prospects in terms of well siting, and can allow hydrogeological mapping and modelling by enabling to regionalize hard-rock aquifer properties.

INTRODUCTION

The link between the hydrogeological properties of hard rocks and the nature of their weathered cover has been recognised for some time now. In particular, the water-retention capacity of alterites has been widely demonstrated. Thus, the main purpose of this paper is not to emphasise the role of alterites, but to demonstrate the existence of a direct link between weathering processes and the permeability of hard-rock aquifers.

This relationship will be supported by data acquired as part of a hydrogeological mapping project sponsored by the Ministry of Construction and Transportation (MOCT) of Korea, including a joint geological and hydrogeological study performed by KIGAM (Korea Institute of Geoscience and Mineral Resources) and BRGM (French Geological Survey) that concentrated on two hard-rock regions in South Korea, namely the Jeonju-Wanju and Gokseong areas, respectively 1000 km^2 and 550 km^2. Observations of the hydrogeological properties of weathering profiles on hard rocks in Korea have complemented the hydrogeological conceptual model for such aquifers already developed in other parts of the world.

The Korean Peninsula, belonging to the southernmost part of the Siberian shield, is essentially composed of Precambrian hard rocks (gneiss and schist) intruded by Jurassic to Cretaceous granite. The groundwater resources are thus mainly associated with both hard-rock and alluvial aquifers.

PRESENTATION OF THE ACQUIRED DATA

Geology

A large part of the two study areas is composed of:

- Jurassic granite, essentially porphyritic and foliated. Foliation is contemporaneous with granite crystallisation, which occurred in a strike-slip ductile shearing context,
- metasedimentary rocks, predominantly schist, amphibolite, and, to a lesser degree, quartzite,
- Precambrian gneiss, including leucocratic gneiss, granite gneiss and porphyroblastic gneiss.

Other rock types, such as Cretaceous conglomerate, shale and sandstone with interbedded tuff, acidic and intermediate volcanics and dykes, crop out locally in both study areas, but are not considered in the present study (KIGAM, 1996 & 1997).

Weathering

Analysis of the structure of the **weathered cover** capping these hard rocks shows that different weathering phases occurred in Korea:

- **an "ancient" weathering phase** affecting the hard rocks down to depths of more than 50 m and resulting in a typical weathering profile, similar to those observed in other regions of the world (Lachassagne *et al.* 2001b; Wyns *et al*. 2003) comprising, from base to top:
  - fresh hard rock,
  - a fissured horizon,
  - saprolite on metamorphic rocks and gruss on granite.

The uppermost part of the original weathering profiles (mottled horizon and iron crust) is not observed, probably because it has been removed by erosion.

- **a more recent weathering phase** affecting only the uppermost few metres of the hard rocks. The rocks, which are neither transformed to clay nor fissured, show yellowish to reddish iron staining.

These weathering processes are believed to have occurred over the whole Korean Peninsula.

The **ancient weathering profile**, the only significant one from a hydrogeological standpoint, is well preserved in low-lying areas, and in major flat-bottomed valleys that can be surrounded by high-elevation rugged hard-rock topography. Geologically speaking, these low-lying areas generally correspond to grabens where alterites have been preserved from previous erosion.

Lineaments

The lineament analysis shows a relatively high density for both study zones, with orientations in good accordance with the other structural observations and, in particular, with the limits of the graben boundaries.

Hydrogeological data

The hydrogeological approach was mainly based on the statistical analysis of data gathered from 676 existing wells as part of both geological and hydrogeological studies ("existing reports") and field surveys performed by KIGAM ("existing wells"). These data include the following: the well's name, coordinates and depth, thickness of the weathered cover (saprolite or gruss), "instantaneous" yield after drilling (which can easily be correlated with transmissivity and thus permeability), etc. One main advantage of this data set, compared to previously published studies (e.g. in Africa or Europe), is the great depth range of the wells, extending to depths of more than 300 m.

Four different data sets were considered, based on information collected from the two study areas (Jeonju-Wanju and Gokseong) combined with data from the "existing wells" and "existing reports". For each data set, statistical processing was performed according to the main lithologies identified in previous chapter. The results appear to be similar for the different data sets.

INTERPRETATION OF BOTH HYDROGEOLOGICAL AND GEOLOGICAL DATA

No evidence is observed to support a relationship between well yield and a) distance to lineament (Fig.1) or b) lineament density.

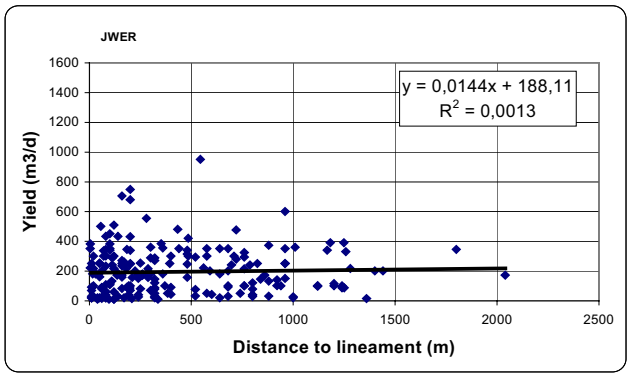

Figure 1. Example of the distribution of well yields as a function of distance to lineaments

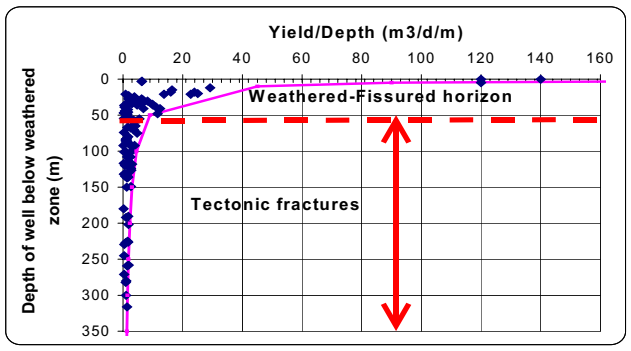

Figure 2. Example of the vertical distribution of specific capacity as a function of depth for wells drilled in zones with a weathering cover (Jeonju-Wanju area, "existing wells", Jurassic granites)

Conversely, a marked relationship is observed between the well's specific capacity (yield (m^3/day) divided by well depth (m) below the base of the alterites) and its depth below the base of the alterites (the first water strike always appears below this horizon), shown as a "classical" sharp decrease with depth (Fig.2). The most interesting point is that this relationship is well expressed for wells drilled in zones where a complete weathered cover is preserved (Fig.2), but is not consistent where, due to erosion, the weathering profile is non-existent (Fig.3).

Despite providing different absolute values of specific yield, similar results are obtained for granite and metamorphic rocks.

CONCLUSION & PERSPECTIVES

It appears that the weathered cover plays a determining role in terms of the permeability of hard rocks, and not only in terms of their water-retention capacity.

The **weathered-fissured** horizon, generally attributed to decompression, that develops within the uppermost tens of metres of the "fresh" basement substratum, is clearly due to weathering processes. It is characterised by fractures (almost horizontal in granite) whose density diminishes with depth. Their genesis is governed by the alteration of philippic minerals (e.g. biotic), which, due to an associated increase in volume, cause the rock to break-up. The coalescence of these horizontal planes at the top of the layer promotes the passage from the weathered-fissured compartment to the alterites. It induces a higher yield of the wells in zones where alterites (and thus the underlying weathered-fissured horizon) are still present than in places where these horizons have been eroded. The **fresh basement** substratum (hard rock) is permeable only very locally associated with tectonic fracturing. Despite local significant yields from certain fractures, the overall specific yield is lower than that measured in the weathered-fissured horizon.

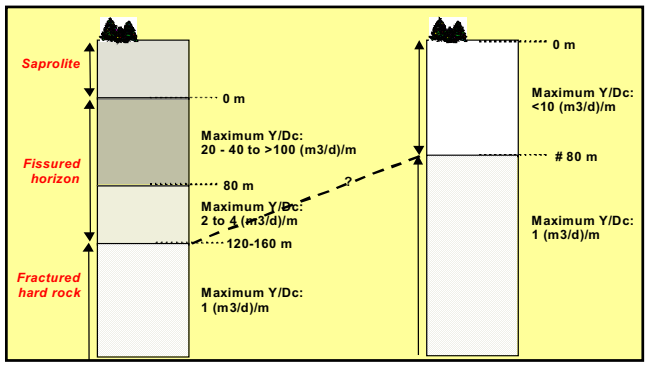

Figure 3. Comparison of the vertical distribution of specific capacity (Y/Dc) as a function of depth for wells drilled respectively in zones with a weathering cover (left) and without (right) (Jeonju-Wanju area, Jurassic granites)

These new results are consistent with observations made in other regions of the world (Africa, South America, Europe, India, etc.). The present extension of such weathered covers is not restricted to tropical countries, but affects large areas worldwide, even if partly eroded. Mapping the geometry of the different compartments making up the aquifer at catchment scale opens up major development prospects in terms of well siting (Lachassagne *et al.* 2001a), and can allow hydrogeological mapping (Lachassagne *et al.* 2001c), water-resource evaluation (Wyns *et al.* 2003), and groundwater modelling (Lachassagne *et al.* 2001b) by enabling to regionalize hard-rock aquifer properties.

REFERENCES

KIGAM- Geological map of Daejeon (1996) and Gwangju (1997): Ministry of Science and Technology, Korea

Lachassagne P, Pinault J-L *et al.* (2001a) Radon-222 emanometry: a relevant methodology for water well siting in hard rock aquifer. Water Resources Research

Lachassagne P, Ahmed S *et al.* (2001b) A methodology for the mathematical modelling of hard-rock aquifers at catchment scale based on the geological structure and the hydrogeological functioning of the aquifer, in XXXI IAH Congress "New approaches characterizing groundwater flow", Munich, Germany

Lachassagne P, Wyns R *et al.* (2001c) Exploitation of high-yield in hard-rock aquifers: Downscaling methodology combining GIS and multicriteria analysis to delineate field prospecting zones. Ground Water:39(4)

Wyns R, Baltassat JM *et al.* (2003) Application of SNMR soundings for groundwater reserves mapping in weathered basement rocks (Brittany, France). Bulletin Société Géologique de France (accepted)

Groundwater exploration in a part of hard-rock terrain of Central India using fracture-pattern modelling

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Groundwater in a hard rock terrain is multivariate because of its relation to topography, depth and extent of weathered material overlying bedrock and because of the size, nature, density, orientation and interconnection of joints and faults. In hard rock terrain, joints, fractures, fault zones and weathered zones are the main sources for groundwater occurrence and movement due to lack of primary porosity in these rocks. To understand the relation of fractures to groundwater occurrence, Larsson integrated deformation model was used in the hard rock terrain of upper Urmil river basin, a part of Bundelkhand region of Central India. The fractures are the surface expression of joints, zones of joint concentrations and faults. In order to understand the significance of fracture pattern and density in groundwater assessment, an integrated map of structure and hydrogeomorphology were prepared using remote sensing data of Landsat 3 imagery. Lineament/features pattern and drainage pattern were analysed using length, density and frequency. The position of water table was measured in 95 observation wells during May-June (Pre-monsoon) and November-December 1999 (Post-monsoon). Lithologic log, groundwater flow directions and water table fluctuations were studied. The present study builds upon the previous studies by analysing the density of tensile fractures in relation to potential groundwater zones. The study area lies between latitudes 24049'10" and 250 10' N and between longitudes 790 28' 45" and 79045" E and falls in Survey of India toposheet nos. 54 p/5, 54 p/9 and 54 O/12. It covers an area of 450 square kilometres. Physiographically, the area has rugged and undulating terrain with few scattered and elongated hill and parallel distinct quartz reefs. The area is gently slopping towards northeast. The climate of the area is semi-arid type. The average annual rainfall of the area is about 1060 millimetres.

The study area is underlain by rocks of Archaean age consisting of Bundelkhand granite and gneiss cut by pegmatite, aplite and epidiorite dykes. Alluvium is present along the lower courses of the river. The granite is coarse to medium-grained; the coarse-grained granite is porphyritic in part and the medium-grained; variety commonly grades into gneiss. Generally two varieties of granites are present; one is pink and the other is grey. Gneiss is associated with the grey variety. The dolerite is medium to fine-grained and forms dykes. The predominant trends of the fractures are NW-SE and ENE-WSW; minor trends are N-S, E-W and NE-SW. Most of the area drainage is fracture controlled. The landforms of the study area were classified as flood plain, alluvial plain, infilled valley, deeply/moderately and shallow weathered buried pediplain, denudation hills and linear ridges. The alluvial/flood plains, infilled valley, and deeply/moderately weathered pediplain are good to very good groundwater potential zones with good yield. Generally, in deeply/moderately weathered pediplain (thickness 5-15 m), dug wells are very common but in shallow weathered pediplain (thickness <5m) bore wells are very common. Most of the agriculture is on the pediplain. In the study area groundwater occurs under both unconfined and semi-confined condition in weathered and fractured granite and gneiss. During May-June 1999, the depth. to water table ranged form 3 to 15 m and during November-December 1999 it ranged form 1 to 10 m. below ground level. NE-SW & NW-SE fractures were identified as tensile and shear fracture respectively in the study area. Apparently, these fractures are the youngest open fractures. Wherever NE-SW & NW-SE fractures densities are high, the weathered zone thickness is greater, the water table fluctuations are small, and the yields of the wells are high. Groundwater zones were identified and classified as very good, good to very good, moderate to good & poor. This modelling may be very useful as methodology for groundwater exploration in complex fractured rock terrain.

Regional transmissivity distribution and groundwater potential in hard rocks of Ghana

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A b s t r a c t : Statistical assessment of specific capacity and transmissivity has made it possible to classify hydrogeologic units on regional scale, and to prepare regional transmissivity anomaly maps for the quantitative characterisation and prediction of borehole yields in hard rock aquifers in Ghana. In general, the rocks pertain to transmissivity classes IV and III, representing low to intermediate transmissivity in magnitude. Mapping out areas of positive transmissivity anomalies delineates prospective zones for groundwater exploration. In such zones, the minimum expected yields range from 35 to 120 L/min in the various hydrogeological units. These yields are 6-15 times higher when compared with probable yields from regions of negative transmissivity anomalies (6 to 10 L/min). Detailed investigations in zones of positive transmissivity anomalies could reveal potential aquifers where large volumes of groundwater could be abstracted.

INTRODUCTION

The disparity in yield and especially, transmissivity in boreholes drilled even in close proximity in the same hard rock type can be very substantial. This could be attributed mainly to effects of heterogeneity and anisotropy that make predictions in hard rock aquifers very uncertain. Assessment based on statistical analysis of the transmissive capacity of aquifers could however, provide information on the general trend and conditions of groundwater resources formation. This is essential for regional policy formulation and regulatory development of groundwater as a natural resource.

As an initial attempt to address the need for a comprehensive regional hydrogeological evaluation to support groundwater development in Ghana, statistical analysis of specific capacity and transmissivity data has been carried out. The prevailing regional trends in transmissivity have been determined and local anomalies delineated to depict prospective zones for groundwater exploration. The effect of the transmissivity anomalies on the probable yields of wells has been expressed based on a general available drawdown.

HYDROGEOLOGICAL BACKGROUND

Hard rocks account for about 80% of the bedrock in Ghana. They comprise a complex of Precambrian igneous and metamorphic rocks, and late Proterozoic to early Palaeozoic rocks of the Voltaian sedimentary system. The Precambrian rocks include the Dahomeyan (gneiss and migmatite with quartz and schist), the Birimian (metamorphosed sediments) with associated granitoid intrusives, and the Tarkwaian rocks (slightly metamorphosed sediments). The rest are the Togo Series (sandstone, quartzite, schist, shale and phyllite) and the Buem Formation (shale, sandstone and volcanic rocks). The Voltaian System consists of consolidated sedimentary rocks mainly sandstone, shale and mudstone, conglomerate and limestone.

The rocks are themselves largely impervious but contain openings along joints and fractures, bedding and cleavage planes that enhance percolation of water to form limited groundwater reservoirs that are structurally dependent and discontinuous in occurrence. Boreholes drilled in such hydrogeologic environments have a wide range of yields, with a significant failure rate. The yield in the Voltaian rocks is highly variable and ranges from 5 to 1200 L/min, with an average yield of 121 L/min. The Dahomeyan gneiss and migmatite record the lowest mean yield of 50 L/min. Data on borehole yields and depths are provided in Tab.1.

Table 1. Yields and depths of boreholes in Ghana

Geological	No. of	Yield (L/min)		Depth (m)	
Formation	Boreholes	Mean	Range	Mean	Range
Granite	767	67	5- 607	37	13-152
Voltaian	779	121	5-1200	42	22-355
Togo & Buem	212	94	7- 525	44	21-146
Birimian & Tarkwaian	213	126	8- 600	54	16-187
Dahomeyan	74	50	9- 200	39	22-122

METHOD OF ASSESSMENT

Statistical methods were used to compare the variability and distribution of the specific capacity and expected transmissivity among the various hydrogeologic units, and to estimate the potential for groundwater abstraction on regional scale. Huntley *et al.* (1992), Knopman and Hollyday (1993), and several authors have extensively discussed the use of specific capacity to estimate transmissivity.

The specific capacity is converted into an index of transmissivity Y, introduced by Jetel and Krásný (1968). The transmissivity index Y is given by the relation: $Y = \log (10^6 C)$, where C is specific capacity (L/s/m). From the index Y, the coefficient of transmissivity, T (m^2/day), is estimated by the conversion equation: $T = 86400\ (10^{Y-8.96})$. The index Y has the advantage when used as a comparative regional parameter as most populations of specific capacity values are log-normally distributed (Knopman 1990). Hence by converting the specific capacity values into index Y, the statistical distribution of the data set becomes a normal distribution and standard statistical procedures can then be used to assess the data.

The range($\bar{x} \pm s$)of the index Y values, which accounts for about 68% of the data set, represents the prevailing transmissivity of the different hydrogeological units. The values outside this interval are considered as anomalies, which may be positive or negative. The interval between $(\bar{x} + s)$ and $(\bar{x} + 2s)$ is defined as the area of positive anomalies, and signifies more prospective zones for groundwater exploration when compared with the area of background transmissivity. On the other hand, the values between $(\bar{x} - s)$ and $(\bar{x} - 2s)$ indicate areas of negative anomalies and these represent less favourable zones. Extreme anomalies can be found outside the intervals $(\bar{x} \pm 2s)$. Krásný (1993) classification scheme, which is based on transmissivity magnitude and variation, is applied to classify the various hydrogeological units. This classification scheme provides a practical quantitative method for evaluating the potential for groundwater abstraction in different areas. It also has the additional advantage of making it possible to express various

regional hydrogeological conditions and their comparison on hydrogeological maps.

The Kriging geo-statistical gridding method was used to prepare transmissivity maps by contouring the irregularly spaced transmissivity data. By establishing the background transmissivity ($\bar{x} \pm s$), areas with positive and negative anomalies were delineated. Fig.1 shows the regional transmissivity trends in Ghana. The effect of the transmissivity differences (anomalies) on the probable yields of wells has been expressed based on a general available drawdown of 5 m. This drawdown has been considered as a practical value for rural, domestic hand-pump based water supply systems (Darko and Krásný 2000).

RESULTS AND CONCLUSION

The quantitative assessment of specific capacity and its modifications has enabled the preparation of regional transmissivity maps, as well as the delineation of local transmissivity anomalies to depict prospective zones for groundwater exploration. The analysis has also made it possible to estimate the probable yield of wells in the various hydrogeological units in Ghana.

The Voltaian sedimentary rocks record the highest mean transmissivity coefficient of 12 m^2/day, with values ranging between 0.3 and 270 m^2/day. These rocks are classified as III-IVd. The Dahomeyan rocks have the lowest mean transmissivity coefficient of 4.5 m^2/day, and belong to transmissivity class IV-(III)c. In general, the rocks pertain to transmissivity classes IV and III, representing low to intermediate transmissivity in magnitude. It could be inferred that petrography might not play much significant role in permeability and transmissivity distribution of the hard rocks in Ghana. Fig.1 is a map showing the general regional trends in transmissivity.

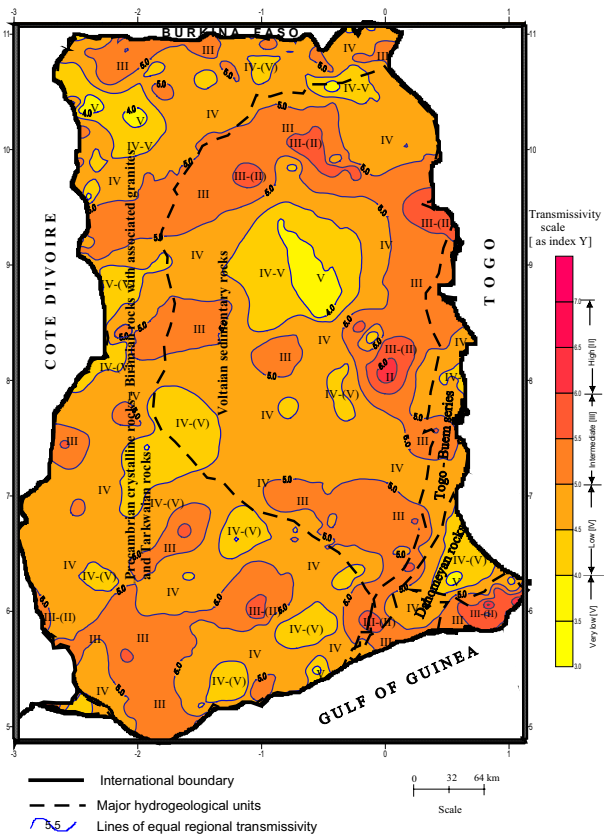

Figure 1. Regional transmissivity trends in Ghana. II-V: Classes of transmissivity magnitude based on Krásný (1993) classification scheme.

In zones of negative transmissivity anomalies, the probable yields range from 6 L/min in the Dahomeyan migmatite and gneiss to 10 L/min in the quartzite, schist and phyllite of the Togo and Buem formation (Tab.2).

Table 2. Expected yields in zones of transmissivity anomalies in hard rocks of Ghana.

Hydrogeologic Unit	Expected minimum yield (L/min)	
	Zones of Negative anomalies	Zones of Positive anomalies
Voltaian	8	120
Granite	6	60
Birimian & Tarkwaian	7	85
Togo & Buem	10	65
Dahomeyan	6	35

The expected yields in zones of positive anomalies range from 35 to 120 L/min in the Dahomeyan and Voltaian rocks respectively. The yields expected from areas of positive anomalies are about 6-15 times higher when compared with yields expected from areas of negative anomalies (6-10 L/min). Detailed investigations in zones of positive transmissivity anomalies could reveal potential aquifers where large volumes of groundwater could be abstracted.

REFERENCES

Darko PK, Krásný J (2000) Adequate depth of boreholes in hard rocks: a case study in Ghana. In: Oliver Sililo *et al.* (eds) Groundwater: Past Achievements and Future Challenges-Proc 30th IAH Congress, Cape Town 121-125

Huntley D, Nommensen R, Steffey D (1992) The use of specific capacity to assess transmissivity in fractured-rock aquifers. Ground Water 30, 3:396-402

Jetel J, Krásný J (1968) Approximative aquifer characteristics in regional hydrogeological study. Věst Ústř Geol Prague 43, 5:459-461

Knopman DS (1990) Factors related to the water-yielding potential of rocks in the Piedmont and Valley and Ridge provinces of Pennsylvania. US Geol Survey Water Resources Investigation Report 90, 4174 52 pp

Knopman DS, Hollyday EF (1993) Variation in specific capacity in fractured rocks, Pennsylvania. Ground Water 31, 1:135-145

Krásný J (1993) Classification of transmissivity magnitude and variation. Ground Water 31, 2:230-236

Occurrence of groundwater in hard-rock terrains of Sundargarh District, Orissa, India

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A b s t r a c t : The present piece of work has helped to understand the role played, lithological, climatological, hydrogeological and hydrogeochemical factors which govern the occurrence, distribution, movement, recharge – discharge and quality of groundwater in the western part of the Sundargarh district, Orissa, India. The subsurface geology obtained from the borehole lithologic logs (Central Groundwater Board) and resistivity surveys reveals that the thickness of the weathered zone varies from 0.95 to 31.0 m in general. The fractured zones occur generally beyond 20 m bgl, which are either charged with or no water. Generally productive fractured zones are restricted within 100 m depth though in rare cases deeper fractures produce higher yields. Basing on the water bearing and water yielding characteristics, the formations in the study area have been divided into three different units, such as consolidated, semi consolidated and unconsolidated formations. The groundwater of the area represents different hydrogeochemical facies such as Ca-HCO_3, Na-HCO_3, Ca-Cl, Na-Cl and Ca-SO_4 among which Ca - HCO_3 type is most dominating. It is well understood that the primary physical control on the occurrence and distribution of various water types in the area may be due to the variation in groundwater residence time.

Though the overall groundwater scenario of Orissa is not very bad, some portions of the districts of Western Orissa like Kalahandi, Bolangir, Sundargarh etc. suffer from acute water scarcity at times due to vagaries of nature and improper management of water resources. In view of the above fact, an attempt has been made for the hydrogeological studies in the western part of Sundargarh district of Orissa, where till today very little work has been done in this regard. The present piece of work has helped to understand the role played by geomorphological, lithological, climatological, hydrogeological and hydrogeochemical factors which govern the occurrence, distribution, movement, recharge-discharge and quality of groundwater in the study area.

The study area forms the western part of the district of Sundargarh, lying towards the northern extremity of Orissa. The area is bounded by the North Latitudes $21^0$45'-22^0 32' and East Longitudes $83^0$32'- $84^0$23' and falls in the Syrvey of India Topo Sheet Nos. 64N/12, 64N/15, 64N/16, 64O/9, 64O/13, 73B/3, 73B/4, 73B/7, 73B/8. Its boundaries in the North – East extend to Ranchi district of Bihar, in the North – West to West upto Raigarh district of Chattishgarh, in the South to Jharsuguda and Sambalpur districts of Orissa. The areas have good network of roads and are connected directly to the district headquarters. The areas under study are characterised by extreme climate with very hot (around 47^0C) summer and very cold (around 4^0C) winter showing large variation in mean daily temperature. About 85% of the annual rainfall are received during the monsoon months. The region is formed extensively of hills and valleys exhibiting an undulating topography. The area is an agricultural dependent one. The surface water does not satisfy the growing needs of agriculture, which further accelerates the use of groundwater in the region.

Major part of the study area is underlain by the Precambrian metasedimentaries belonging to the Gangpur Group which comprises of mica-schist, carbonaceous phyllites, quartzites and granite gneisses intruded by younger granites (Sundargarh granites). Only a small portion around Hemgir in the southwestern part is occupied by the Lower Gondwana sediments comprising of sandstone, shale, grits, conglomerates and clays with coal-bearing horizons. Subsequent to the Gondwanas no other major lithologic units has been developed in the area except lateritisation and formation of soil and alluvium of recent origin occurring as narrow patches. Depending upon the distribution of major lithologic units, physiographic setup, extent of weathering and fracturing of the hard rocks, the groundwater development potentials of the area vary widely.

From the study of the lithologs in different blocks in the study area, it is found that due to variations in geological formations in the area, the aquifer characteristics vary and so also their yield capacities. In general the top soil varies in thickness from 0.7 m to 7 m, except at one area (Sargipalli), where a thick zone of topsoil / alluvium (20.3m thick) is found representing a palaeochannel deposition. The different fractured zones present in various lithounits make them water bearing and hence are important from hydrogeological point of view (Tab.1)

The subsurface geology obtained from the bore-hole lithologs (Central Groundwater Board) and resistivity surveys reveals that the thickness of the weathered zone varies from 0.95 to 31.0 m in general. The fractured zones occur generally beyond 20 m bgl, which are either charged with or no water. Generally productive fractured zones are restricted within 100 m depth though in rare cases deeper fractures produce higher yields.

Table 1. Depth Range & Yield Characteristics of Fractured Zones

Litho Units	Depth Range Of Saturated Fractures (m bgl)	Saturated Fractures Up to 60 m	Saturated Fractures Up to 60-100 m	Saturated Fractures Up to 100-150 m	Saturated Fractures Up to 150-200 m	Cumulative Yield Range (L/s)
1. Granite & Granite Gneiss	10-199	1 to 3 sets, very common	Mostly 1 set, very common	Mostly 1 set, less common	2 sets. Only in one well	Negligible – 9
2. Mica Schist	13.2-178.9	1 to 4 sets, very common	1 set, less frequent	1 set, less frequent	1to 2 sets, rare	Negligible – 7
3. Phyllite	18-99.5	1 to 4 sets, very common	1set, rare	--	--	2 – 4
4. Sand Stone	12.1-134	2 to 4 sets, frequent	2 sets, common	1set, rare	--	1.6-11.5

The vertical electrical soundings conducted at different points in the study area revealed typically 3-layered and 4-layered situations. The top layer is a mixed sediment layer (soil zone) with varying contents of sand, silt, clay extending maximum up to a depth of 13ms from ground level with resistivities ranging from 11ohm – m to 700 ohm-m. In a three layer case the second layer represents the weathered or fractured zones extending from 3.5 to 37metres below the ground level in general, but even more in some cases. The weathered material is granitic or quartzitic in compositions. The second layer represents comparatively lower resistivities between 5 to 500 ohm-m and the 3rd layer is the compact bed rock showing very high resistivities having little or no water. So in a 3-layered case the second layer is interpreted as the potential horizon from where a good amount of water can be extracted. In the 4-layered cases, the second layer is similar to that found in a 3-layered case. The 3rd layer generally shows less

resistivity values (100-500 ohm-m) which is interpreted as the fractured zone & is water bearing. However, this 3rd layer has relatively more resistivity values than the 2nd layer. The 3rd layer extends from a depth of 27 to 45 metres below the ground level. At some locations the fractured zone is totally absent within the range of sounding or present in place of the weathered zone even. The third layer (in case of 3-layered case) or the fourth layer (in case of 4-layered case) represents the hard rock / basement except at Sagjore (Subdega Block) & Barangakochhar (Bargaon Block) where both the third & fourth layers have been interpreted as fractured zones and no basement was encountered in such areas within the depth range of sounding. The areas where basement was encountered shows very high resistivities values of >500 ohm-m to ∞ indicating complete absence of water. Therefore the second layer represented by the weathered / fractured zone in a 3-layered & 4-layered case and the third layer represented by the fractured zone in a 4-layered case are very important in locating well sites in the study area.

The lineament and hydrogeomorphological maps prepared from the IRS-IA (LISS-II) imagery reveal that the extensions of lineaments in the buried pediments and valley fills may serve as excellent groundwater potential zones in the area. From the lineament map it is inferred that better yields are received from the areas of NW-SE trending lineaments, mainly towards the southwestern and eastern portions of the area which also represent comparatively higher lineament density. The hydrogeomorphological study by remote sensing techniques supported by limited ground truth studies reveals that groundwater potential is moderate to good along the linear valleys of structural hills, intermontane valleys, buried pediments, weathered buried pediplains and the fractured zones in the pediments. Also it is marked that the areas of intersection points of lineaments serve as hydropotential zones.

Basing on the water bearing and water yielding characteristics, the formations in the study area have been divided into three different units, such as consolidated, semi consolidated and unconsolidated formations. In the consolidated formations groundwater occurs in the weathered/semi weathered residuum and deeper fractured zones. In semi consolidated formations it occurs in the weathered residuum as well as in the pore spaces of sandstones. The unconsolidated formations of recent origin are found in narrow patches where groundwater occurs at shallow depths due to primary porosity which can be developed by open wells.

Highly weathered and jointed granitic rocks occurring in the undulating plains form potential aquifers in the hard rock terrain. Mica-schists and phyllites having very thick weathered residuum form moderately potential shallow aquifers. Friable and fractured sandstones of the Barakars and Kamhis often constitute moderately potential shallow and deeper aquifers.

In the Gibbs (1970) diagram all the samples (109 analysed) fall within the rock-dominance field indicating that the overall lithology of the area is responsible for different constituent ions in the groundwaters of the area. The physical parameters such as colour, odour and taste etc. of the groundwaters of the area are not generally objectionable. The variation of pH values between 7.05 to 8.85 indicates the water to be nearly neutral to slightly alkaline. The EC ranges from 160 to 1100 μ mhos/cm at 25^0C, but the values remain within 1000 μ mhos/cm in a majority of cases except two samples, which show higher values due to higher TDS. EC of groundwater samples increases with increase in TDS, total hardness, alkalinity, chloride, sodium and potassium Normally almost all water samples remain within the range of soft to hard category except two localities which are of very hard type as per the classification system of Sawyer and Mc Carty (1967). Fluoride content of the groundwaters of the area shows positive correlation with bicarbonate and negative correlation with calcium supporting the views of Handa (1975) and Ravi Prakash *et al.* (1989).

Comparison of the results of the chemical analysis of the groundwaters from shallow and deeper aquifers with the standard specifications of ISI (1983) reveals that the water is normally suitable for drinking and other domestic purposes, barring few exceptions. However it is a general observation that the waters from deeper aquifers have better quality than that of the shallower ones. The study of the suitability of the groundwater for irrigation point of view further confirms that most of the well waters fall under good to excellent category for irrigation with few exceptions.

The groundwater of the area represents different hydrogeochemical facies such as Ca-HCO_3, Na-HCO_3, Ca-Cl, Na-Cl and Ca-SO_4 among which Ca-HCO_3 type is most dominating. This fact is also evidenced from the hydrogeochemical facies distribution map and the spatial concentration diagrams (three dimensional) prepared with the help of SURFER software package.

It is evident that different hydrogeochemical facies (water types) are not restricted to particular areas. Calcite and dolomite dissolution are the dominant chemical processes involved in the generation of Ca-HCO_3 type water (Plummer *et al.* 1978; Bunsenberg and Plummer 1982). The Ca-SO_4 type associated with higher concentration of SO_4 might be derived from sulphatic fertilisers, sulfide mineral oxidation, H_2S oxidation or a combination of the above processes (Scanlon 1989). The process of cation exchange and sulphate reduction are used to explain the production of Na- HCO_3 type water. The origin of Na-Cl and Ca-Cl types cannot be determined from the available data. It is well understood that the primary physical control on the occurrence and distribution of various water types in the area may be due to the variation in groundwater residence time.

REFERENCES

Bunsenberg E, Plummer LM (1982) The kinetics of dolomite in CO2-H2O Systems at 1.5 to 650 C and 0 to 1 atm Pco2. Am J Sci 282:45-78

Gibbs RJ (1970) Mecahnisms of controlling world's water chemistry science 170:1088 p

Handa BK (1975) Geochemistry and Genesis of fluoride containing groundwaters in India. Groundwater 13:3:275-281

I.S.I (Presently known as Bureau of Indian standards) (1983) Indian Standard Specifications for drinking water, IS: 10500

Plummer LN, Wigley TML, Parkhurst DL (1978) The kinetics of calcite dissolution in CO2 water systems at 50 to 600 C and 0.0 to 1.0 atm CO2. Am J Sc 278:179-216

Ravi Prakash S, Subba Rao N, Krishna Rao G (1989) Fluoride in groundwaters of Paravada area near Visakhapatnam, Andhra Pradesh. Hydrol Jour of IAH 12:3:108-115

Sawyer CN, Mc Carty PL (1967) Chemistry for sanitary engineers, 2nd ed, Mc. Graw-Hill, New York, 518p

Scanlon BR (1989) Physical Controls on Hydrochemical Variability in the Inner Bluegrass Karst Region of Central Kentucky; Groundwater 27(5):639-646

Experimental catchment in a hard-rock environment: application to the Guadarrama Mountain (Central System, Spain)

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A b s t r a c t : This paper presents the main results of the qualitative and quantitative research on water resources in the High Lozoya Catchment. A chemical quality control network was established. The chemical analyses show that there is a closely linked between hydrochemical facies and the lithology of the terrain where the points are located. The waters in hard rocks have a sodium-bicarbonate character, and occasionally calcium. The others in sedimentary aquifer are mainly calcium-bicarbonate composition with higher salinity than that circulating on hard rocks. Despite this region has important cattle raising activity, it does not seem to have a significant influence on the chemical quality of its water resources. An experimental sub-catchment has been selected for the runoff study. Simulation was made by means of a precipitation-runoff model implemented with a quantitative approximation to quantify the snow effect on surface runoff. The model was calibrated achieving the highest fitting grade between the real and the simulated hydrographs.

BACKGROUND

Introduction

The High Lozoya Catchment is an intramontane depression with a rhomboidal shape, which is located in the Guadarrama Sierra of Spanish Central System (Fig.1). This area covers approximately 250 km^2 and it is one of the areas of the Madrid Region with greatest ecological interest.

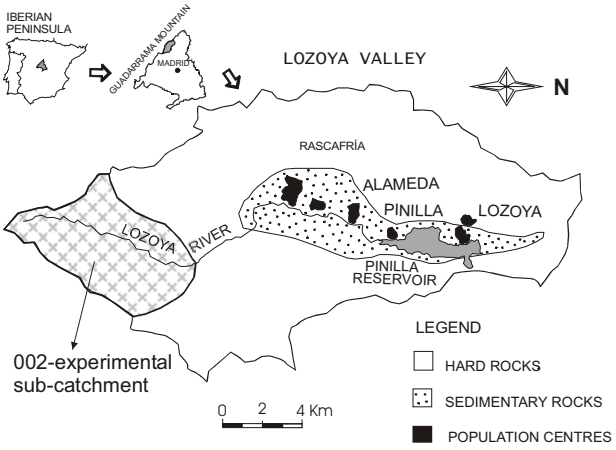

Figure 1. Simplified geological map of the High Lozoya Catchment

The climate of this area is Continental Mediterranean type, with long, cold winters, and short, dry summers. Both temperature and precipitation show a clear variation with the altitude. The average yearly temperature is between 6º and 14º C. The annual precipitation is between 600 and 900 mm/year in the lowest areas and between 1000 and 1500 mm/year in the areas situated at more than 2000 m above sea level, reaching as much as 2000 mm/year in some places (CAM 1985).

Hydrogeological Framework

There are two general lithological units over the High Lozoya Catchment (ITGE 1991) (Fig.1). One is formed of hard rocks, mainly glandular granitic gneisses. The Hercynian Orogeny has deformed all these metamorphic rocks. Sedimentary rocks filling a sedimentary basin form the other lithological unit composed by limestones, marl and sandstones of Cretaceous age appear first; and detritic rocks of Paleogene age and thin-layered Quaternary sediments. Sedimentary rocks occupy the central area, while hard rocks constitute the edge of the sedimentary basin and the areas of the slope of the catchment.

Hard rocks have a secondary porosity originated by alteration processes and joints (mainly of tectonic origin) that allow the circulation of small amounts of water. At greater depths, the hard rocks are practically impervious, because of closing fractures produced by the pressure of overlying rocks.

The weathering of metamorphic rocks produces shallow aquifers, which generally have a thickness of less than 10 meters. They are small phreatic aquifers that discharge in springs and streams. The scarce water resources in these aquifers are used to supply water to cattle raising and some country houses.

Sedimentary deposits have a thickness that can reach 100 m and constitute an unconfined aquifer. On the top, there are karstified Cretaceous limestones. The high permeability of this aquifer facilitates its exploitation but, at the same time, makes it more vulnerable to contamination.

There are many installations for water abstraction located on hard rocks in the High Valley of Lozoya because of their low yield, and of the scattered distribution of potential users in the area (towns and extensive cattle-raising). The types of springs and wells usually found on hard rocks, according to the inventory made in the valley are: up-fault springs, springs located in the weathering-rock interface, dug wells located in weathering zones.

The main aim of this work is to achieve the description and assessment of hydrogeochemical characteristics of the water in this area and the modelling of precipitation-runoff processes in an experimental hard rock sub-catchment.

FEATURES

Hydrochemistry

Broadly speaking, in most cases, the water shows a very low or low salinity (with conductivity below 200 µS/cm), with pH values around 6-7, and calcium-bicarbonate hydrogeochemical facies.

However, according to the Schoeller-Berkaloff Diagram (Fig 2), there are two types of water depending on the lithology of the terrain where wells, springs and streams are located. On the one hand, springs, wells and rivers in hard rocks have water with low salinity, with conductivity values between 14 and 150 µS/cm, and less than 42 and 8 mg/L of bicarbonate and calcium respectively. On the other hand, springs and wells on the sedimentary aquifer have conductivity values between 42 and 380 µS/cm. Calcium and bicarbonate, as major ions, reach values up to 60 and 250 mg/L respectively.

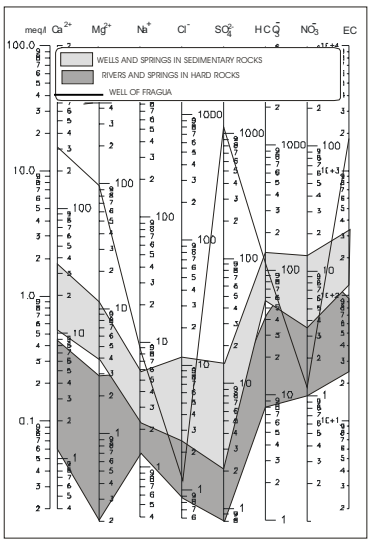

Figure 2. Chemical values in mg/L excepting EC (electrical conductivity) in µS/cm

Another clear difference between these two types of facies is the content of Mg^{2+}. Groundwater in hard rocks has concentrations under 3.5 mg/L, while groundwater, circulating across sedimentary rocks has in every case concentrations above 3.5 mg/L, and can reach up to 18 mg/L.

Both hydrogeochemical facies have in common a low content of sodium, with maximum values of 8 mg/L. Content of chloride has a higher variability, having maximum values of 25 mg/L in the water flowing on sedimentary rocks and 15 mg/L on hard rocks.

Fig.2 shows the analyses of a drilled well (Well of Fragua), which is placed on limestone, and the chemical quality of its water notably differs from other springs and wells. It is a well 127 m deep that collects water from the Cretaceous aquifer. It has high salinity with values between 2,070 and 1,480 µS/cm and calcium sulphate hydrogeochemical facies. The content of sulphate and calcium is rather high, having maximum values of 1,470 and 370 mg/L respectively.

Precipitation-Runoff Model

An experimental sub-catchment covering 38.32 km^2 and made up solely of hard rocks and their derivative surface formations was selected within the High Lozoya Catchment (Fig.1). All the area presents a very irregular topography, and due to its high altitude - from 1,300m to 2.428m-, it is mainly covered by snow in the winter. Modelling of precipitation-runoff processes was made using the CHAC program, an aggregated hydrological model developed by the Hydrographic Studies Centre of CEDEX. Input data were: rainfall, evapotranspiration, soil moisture and field capacity. Output data were the inflows produced by means of the runoff foreseen by the model. The model simulates over time the complete hydrological cycle. It establishes water balances between the different stages that occur from the precipitation to the return of the water to the river, that is, the different stages of the hydrological cycle.

The simulation was carried out in the 002-experimental sub-catchment for the water year 2000-2001. Meteorological data have been obtained from 2462-Navacerrada and 3104-El Paular which are the nearest meteorological stations. Field capacity has been estimated by the analysis of the soil samples collected during the field campaign. The model has been calibrated with the gauging-measures obtained in field during the simulation period. Our aim is to get the best fitting between the hydrograph simulated by the model and the real hydrograph by means of consecutive model runs and calibration of some parameters of the CHAC program.

A difficulty had to be overcome in this process (Fig.3a) during the First Simulation Hypothesis. That was the impossibility of the immediate conversion of the precipitation in snow form to runoff. The total precipitation measured by the pluviometer corresponds both to rain and snow, but the water from rain and snow does not reach the gauging-station at the same time. We have considered that rain reach the gauging-station within the same month in which precipitation occurs, while snow remains until the melting time, then increasing the runoff formerly produced exclusively by rain. To take the snow melt/accumulation effect into account, several attempts were made until reaching a match between the simulated hydrograph with the real one. This lead us to obtain the snow melting percentages that are shown in the table attached to the hydrograph (Fig 3b).

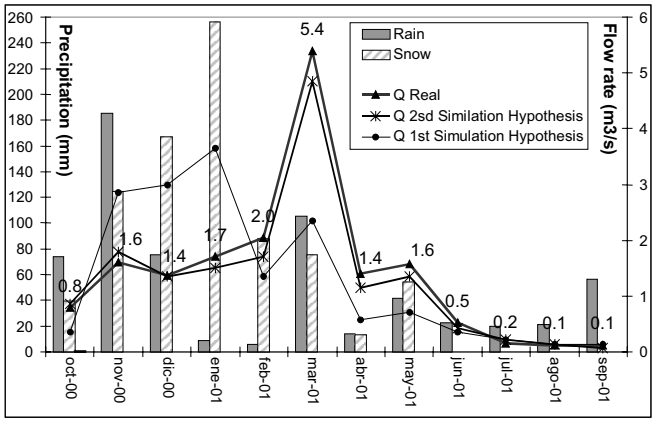

Figure 3a. The best fitting taking into account the snow effect (Second Simulation Hypothesis)

Water year 2000-2001	Precipitation (mm)	Rain (mm)	Snow (mm)	Total Snow (mm)	Snow Melting %	Melted snow (mm)	Accum. Snow (mm)	Available Liquid Precipitation (mm)
Oct-00	113	74	39	39	1	0.4	39	74
Nov-00	309	185	124	163	1	1.6	161	186
Dic-00	242	75	166	228	10	32	295	18
Jan-01	264	8	256	551	19	104	446	113
Feb-01	94	6	87	534	26	139	395	145
Mar-01	181	105	75	471	61	287	183	393
Apr-01	27	13	13	197	50	98	98	112
May-01	96	42	54	152	77	117	35	159
Jun-01	23	23	0	35	100	35	0	58
Jul-01	20	20	0	0	100	0	0	20
Aug-01	21	21	0	0	100	0	0	21
Sep-01	56	56	0	0	100	0	0	26
Total	**1449**	**632**	**817**					**1449**

Figure 3b. Snow effect quantification table corresponding to best fitting by means of Snow Melting % adjustment

With this simulation, in which we have used a precipitation-runoff model implemented with a quantitative approximation to quantify the snow effect on surface runoff, we have improved our knowledge on the behaviour of the 002-experimental sub-catchment as a hydrologic system.

ACKNOWLEDGMENTS

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REFERENCES

CAM (1985) Comunidad Autónoma de Madrid 1985. Mapa fisiográfico de Madrid. Escala 1:200.000. Consejería de Agricultura y Ganadería. Memoria 42 pp Madrid

IGME (1991) Instituto Tecnológico Geominero de España 1991. Geological maps of Spain. 1:50.000. Hoja nº 484 (Buitrago de Lozoya). 105 pp Madrid

Fracture analysis for groundwater targeting in the Kamieskroon region, South Africa

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A b s t r a c t : The standard methods to predict the location of groundwater targets in basement aquifers have been adopted together with fracture frequency and fracture intersection studies. Fracture frequency and fracture intersection analyses were conducted by studying aerial photographs and Landsat images. Basement rocks lack primary porosity, and the conduits for groundwater are essentially fractures, faults and joints. In the region of high fracture frequencies and high rates of fracture intersections, the exploitation potential for groundwater is most likely to be high. The methods employed aim to locate these high fracture frequency zones and high fracture intersection zones. Kamieskroon is situated within the semi-arid Northern Cape Province of South Africa. The area has a complex geological history of multiple folding, faulting and syntectonic granitic intrusions. Deformation commenced during Late Proterozoic times (ductile deformation), and continued through to the Phanerozoic (brittle to semi-brittle deformation). The hydrogeology is inherently complex, with a regional fractured crystalline basement aquifer and a local fractured crystalline aquifer overlain by a weathered regolith aquifer. Local groundwater flow paths vary, and the regional flow direction is to the north. In this region, N-S and WNW-ESE directed fractures are identified as the most abundant. A N40^{0}W directed maximum compressional stress is observed during most of THE Cenozoic, indicating that these features might be open. Fracture frequency and fracture intersection zones compare well with existing high yield zones for the area.

INTRODUCTION

Groundwater in the basement aquifers of the Northern Cape is associated with geological structures such as faults and shear zones. These structural features have a marked influence on groundwater flow processes. More often than not, higher yielding boreholes in such environments would be associated with a certain stress regime and fracture orientation. By determining the neotectonic (present day) stress regimes, groundwater practitioners can be assisted in predicting the most likely groundwater flow patterns and reservoirs.

STUDY AREA

The focus of this study is in the Namaqua Province, which forms part of the crystalline basement in the Northern Cape and southern Namibia. The water supplied to the communities in the Kamiesberg region is solely from boreholes.

The area under investigation forms part of the Namaqualand Metamorphic Complex (NMC) that has been intensely studied and mapped. The Proterozoic Namaqualand Metamorphic Complex (NMC) encompasses a large region. The study area consists of metasedimentary- , metavolcanic- as well as intrusive

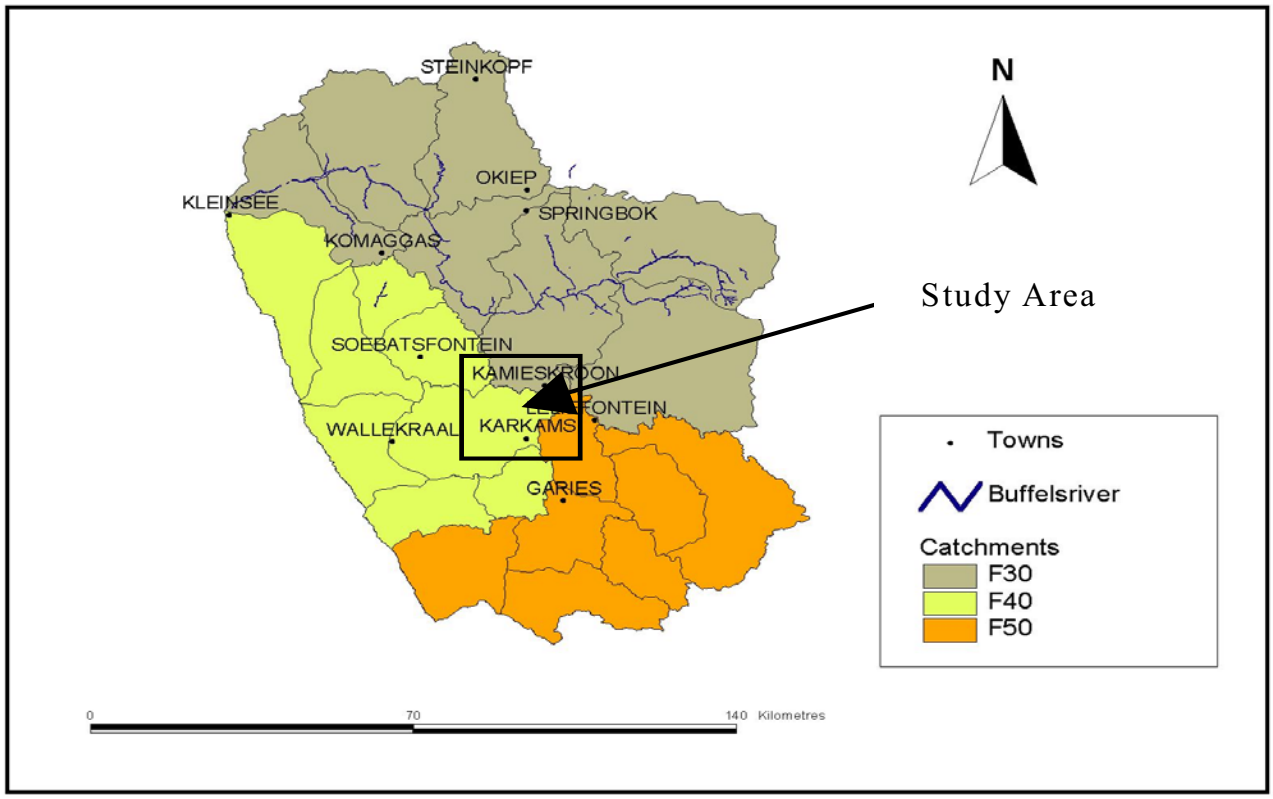

Figure 1. Locality map of the Target area, the Kamiesberg region

rocks which are mainly gneissic in character. The NMC is a polyphase deformed and metamorphosed gneissic terrain consisting of paragneisses that are derived from various sedimentary and volcanic rocks, which have been intruded by a great variety of igneous rocks. Gibson *et al.* (1996) relates the complex deformational and intrusive history to two main ororgenic events at ~1200- 1250 Ma and ~1030 Ma.

METHODOLOGY

Aerial photographs, topographic maps, published geological maps and satellite images were part of the remote sensing analysis. A reference point was used to mosaic the 75 traced sheets along their borders. All the sheets of the different flight plans were traced onto a single sheet that covered the respective region. This single sheet was transferred onto a digitizing board and traced by using the MapInfo computer-drawing program. The aerial photographs were scanned at 600 dpi resolutions and resampled to 300 dpi in order to achieve file size reduction without the loss of image resolution. The scanned images were georeferenced, projected and subsequently mosaicked into a single image.

The observed lineaments from both the aerial photographs and Landsat images were merged in ERDAS, and grid files were created in Rockware. The grid files were subsequently contoured in Surfer to create lineament frequency and lineament intersection maps. The mosaics of all the data layers were incorporated into the Arc View 3.1 GIS program.

The lineament frequency and lineament intersection maps are based on the aerial photographs and Landsat interpretation. The grid files were created and contoured in Surfer software, which also produces the lineament frequency and lineament intersection maps. The maps identify areas of high fracture frequency and areas of highest fracture intersections.

The general direction of principle stress can also be obtained from the rose diagram trends according to the classical interpretation. The maximum principle stress (σ_1) is located to the NW- SE; minimum principle stress (σ_3) is located to the NE- SW. The intermediate principle stress (σ_2) is vertical implying a strike slip environment.

The groundwater state is derived from field investigations and data off the national groundwater data base (NGDB). A series of analyses consisting of borehole yield and borehole depth has been investigated.

CONCLUSION

On a local scale, there is a wide variation in the orientation of the stress direction, whereas regionally, there is a combination of stress directions.

The application of remote sensing techniques, aerial photographs and Landsat images allows an identification and understanding of the fracture systems. The fractures systems are the result of structural (ductile and brittle) deformation.

The groundwater state recorded from the NGDB reveals that 86% of the boreholes in the Kamiesberg region are low yielding (< 1L/s) or dry and 90% of the boreholes are drilled in the weathered overburden (40- 80m). There is no direct link between the borehole yield data, fracture frequency and fracture intersection maps for the region. The higher yielding zones are located in the southern and western parts whilst the high fracture frequencies and intersections occur in the northeastern and southern parts of the region. There is a lack of reliable data to determine a confident groundwater state of the Kamiesberg region.

The data from the study, i.e. lineament mapping, fracture frequency, fracture intersection, neotectonic study and groundwater state, provides useful information to identify potential groundwater resources in the Kamiesberg region. The potential groundwater resource areas that have been identified are the areas in and around the towns of Kamieskroon, Karkams and Leliefontein. These areas are located in zones of highest fracture frequency and fracture intersection. The town of Kamieskroon was selected for additional research primarily because of its data availability and to add confidence to the conceptual model inferred. The town has eight functioning boreholes, three shallow and five deep boreholes. The shallow boreholes are aimed at the weathered zones and the water is reasonably fresh (pers. comm. P Roux). The deep boreholes are drilled along the north-northwest trending lineament/ fracture system and the water has a 'brackish' taste. The shallow boreholes are used periodically due to the limited storativity of the weathered overburden whilst the deep boreholes are pumped continuously (op cit.). The shallow boreholes have a mean yield of 1.6 L/s while the deep boreholes have a mean yield of 1.28 L/s. These areas, both weathered overburden zones and NNW- SSE lineament/ fracture systems, have been identified to be the optimal zones for potential groundwater resources in the Kamiesberg region.

A neotectonic study, recorded from the fractures, shows a northwest to southeast (NW- SE) orientated maximum principle stress (σ_1) for the region. This implies that the northwest-orientated fractures would be regarded as the 'open' fractures. The pegmatite intrusions fill the east-west (E-W) fractures and the dykes fills the north-northeast to south-southwest (NNE-SSW) fractures. Analysis of a confident neotectonic study in the Kamiesberg region is hampered by the lack of recent geological deposits (Quaternary).

REFERENCES

Gibson RL, Robb LJ, Kirstes AFM, Cawthorn RG (1996) Regional setting and geological evolution of the Okiep Copper District, Namaqualand, South Africa. S Afr J Geol 99(2):107-120

Hydrogeometrical aspects of the gabbro of the Beja Aquifer System

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A b s t r a c t : The gabbro of the Beja Aquifer System (GBAS) is one of the most important hard-rock aquifers in the south Portugal. Duque (1997) made the first approach to define the regional groundwater flow model. During that study the available hydrogeological data were scarce and not reliable. The definition of the aquifer geometry and anatomy was a very hard task. Recent research enabled to get new hydrogeologic data, namely almost 1000 borehole log data all over the aquifer. These new hydrogeological data allow a re-definition of the "hydrogeometry" of the GBAS in some locations and now it is possible to define more accurately the vertical structure and the bottom of the aquifer as well as some geological limits. These new hydrogeometrical indicators play an important role in the re-definition of the old groundwater flow model and consequent implementation of a new reliable nitrate transport model.

PURPOSE

Duque (1997) made the first attempt to model the groundwater flow in the gabbro of the Beja Aquifer System (GBAS) with the modelling environment MODIME (Zhang *et al.* 1993), which includes the MODFLOW package (McDonald and Harbaugh 1988). The hydrogeological data available in 1997 were very scarce and not trustworthy. Now the research aims include the implementation of a contaminant transport model with MT3D package. Today new hydrogeological data are available, namely more than 1000 borehole log data all over the aquifer. These data allow a robust re-definition of the geometry of the GBAS, namely estimation of the aquifer bottom, distribution of the aquifer thickness, aquifer border and the standard vertical aquifer structure. GBAS is the most important hard-rock aquifer in the south Portugal and covers almost 347 km^2 of area (Fig.1). It is implanted in a NW-SE igneous-metamorphic structure with ofiolitic affinities. The main rocks are gabbro, amphibolites and serpentinites, all of them intensively weathered and fractured. The groundwater yields are very high when compared with the aquifers around and have an average yield of 5 L/s, untill a maximum of 36 L/s (Duque and Almeida 1998). GBAS is a free type shallow aquifer (sometimes with some confinement).

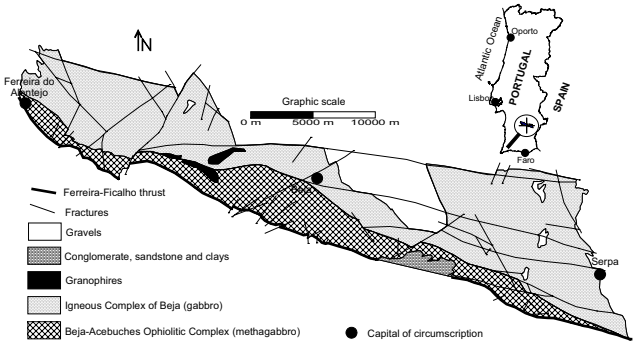

Figure 1. Map of the gabbro of the Beja Aquifer System (GBAS)

In terms of water balance, GBAS is in equilibrium. The recharge deficits are supplied in the rainy years and the water excess is discharged by runoff, by some natural springs and by baseflow to several permanent streams and rivers. The recharge comes directly from precipitation. Duque (1997) calculate the recharge, based on the groundwater abstraction inventory, as almost 4% of the annual precipitation (540 mm/year). However, in 2002, after a detailed inventory based on the recalculation of the total groundwater abstraction, the recharge was assessed about 8.3% of the total annual precipitation, i.e. almost the double taken in account in 1997. The groundwater of the system flows through independent and impermeable blocks giving raise to high gradient heads. Nowadays GBAS supplies almost all agriculture and cattle breeding. The human water supply in most rural villages also depends on GBAS groundwater. Till some years ago this aquifer almost supply the city of Beja (about 40,000 inhabitants).

NEW AVAILABLE BOREHOLE DATA

To assess the GBAS geometry new data were available as follows: by consulting almost all drilling companies operating in the area since 1952, there were achieved data from 1620 drilled wells (cased or not cased). However, only 1001 data were considered good enough for hydrogeologic purposes. All borehole data refer to many drilling and hydrogeologic parameters, but regarding the achievement of the main goals, it was considered: well deepness; weathered zone deepness; fractured zone deepness; aquifer bottom deepness; first, second and third productive deepness.

AQUIFER BORDER REDEFINITION

The geological contacts between the GBAS and the vicinity rocks are: in the northern part with porphyric rocks; in the southern part with a large schist complex; in the western part with the same last schists and by a upper clayey sedimentary Miocene deposits; in the eastern part with marbles intercalated by schists. All geological contacts are almost vertical except for the southern contact, where there is a slope component, which is represented by an important regional thrust - Ferreira-Ficalho Thrust - (Fonseca 1995). The previously defined aquifer border was not too faulty, but considering the new borehole data, it is possible to improve its accuracy. The old border was now re-defined in some particular locations as shown in fig.2. There were six sites where the aquifer border esperienced more significant changes.

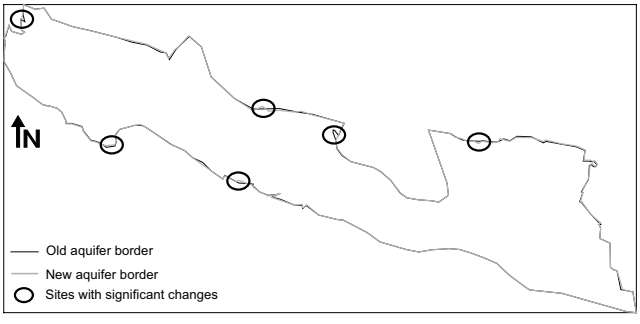

Figure 2. Significant aquifer border changes performed in GBAS

GBAS VERTICAL STRUCTURE MODEL

In GBAS, the well deepness has a wide range, but the median is about 32 m. The weathered zone ranges from the surface till 50 m deep, however its median is 12 m deep. The fractured zone also ranges from the surface till 73 m deep, but the median is 26

m deep. The median of the aquifer bottom is also 26 m deep. Usually GBAS has 1, 2 or 3 productive levels represented by the respective medians in the depths of 12, 20 and 26 m. The statistical results of the vertical structure are presented in fig.3. The GBAS top soil is constituted by montmorillonitic clays and usually is of a 2 m thickness. However, this layer was included into the weathered zone. These results give substantial evidence about the highly superficial conditions of GBAS. Fig.4 shows a vertical cross section of the hydrogeologic structure of the GBAS.

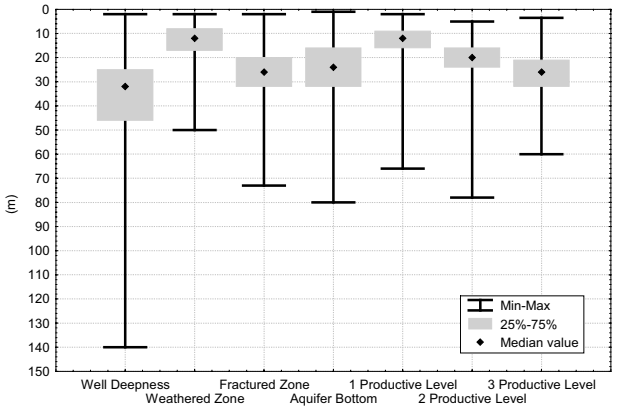

Figure 3. Statistical results of the vertical aquifer structure

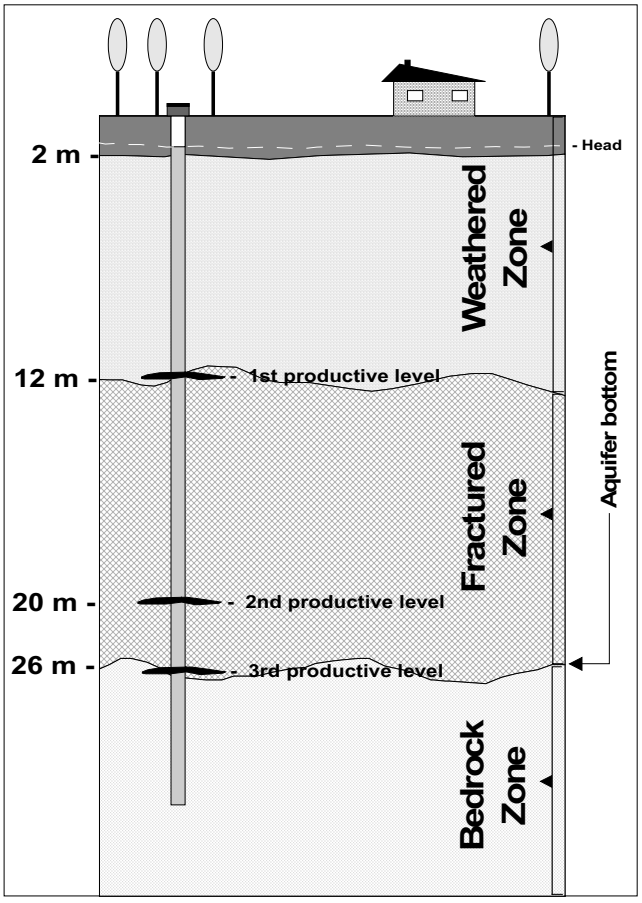

Figure 4. GBAS: Hydrogeologic vertical cross section

GBAS THICKNESS DISTRIBUTION

As any hard-rock aquifer, GBAS seems to have a random thickness distribution, due to the randomness and anisotropy of fracturing and chemical weathering processes. In aquifer modelling, namely in contaminant transport, the definition of the aquifer thickness distribution is an essential step to implement a model. The GBAS thickness distribution was interpolated by kriging and its semi-variogram was modelled. Fig.5 shows the thickness distribution and the model semi-variogram parameters. The white spots are related with thin aquifer zones, otherwise and the darker spots are related with places where the aquifer thickness is higher.

The occurrence of high yields does not have a direct relationship to high aquifer thickness.

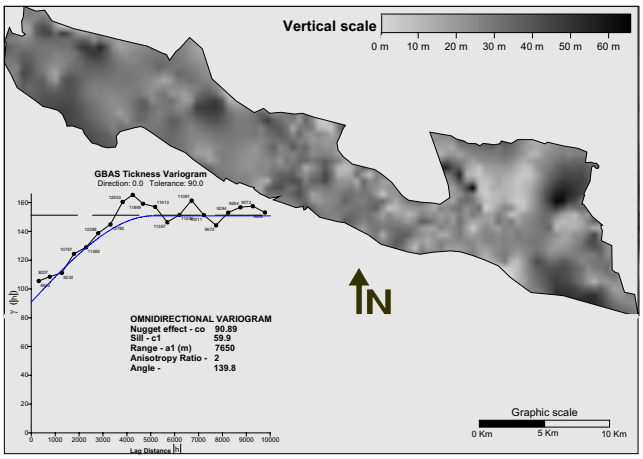

Figure 5. Kriging distribution of the GBAS thickness and the semi-variogram modelled

CONCLUSIONS

New hydrogeologic data allowed the best definition of the aquifer border and vertical structure and thickness distribution within the GBAS. The general data are based on almost 1000 drilled borehole logs with diverse hydrogeological information. So, today significant hydrogeologic knowledge is available, namely, the new aquifer border design, standard vertical aquifer structure, stochastic distribution of the GBAS thickness.

The knowledge of the geometric 3D features of the GBAS will be used in modelling, namely in contaminant transport (nitrates for instance).

AKNOWLEDGEMENTS

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REFERENCES

Duque J (1997) Hydrological characterization and mathematical modelling of the Gabbro of Beja Aquifer, (in Portuguese), M.Sc. Science Faculty of the University of Lisbon, Lisbon, 220 pp

Duque J, Almeida C (1998) Mathematical modelling of the Gabbro of Beja Aquifer. (in Portuguese). In: Proc 4th Water Congress. FIL. Lisbon. CD-165

Fonseca P (1995) Study of the variscan suture in the SW Iberia in the Serpa-Beja-Torrão, Alvito-Viana do Alentejo regions, (in Portuguese), Ph.D., Science Faculty of the University of Lisbon, Lisbon. 325 pp

McDonald MG, Harbaugh AW (1984) A modular three-dimensional finite-difference ground-water flow model, Scientific Publications CO., Washington, 528 pp

Zhang Y, Zheng C, Neville CJ, Andrews CB (1993) MODIME-Integrated modeling evironment for MODFLOW, PATH3D, and MT3D, SSP&A Softwere-S.S.Papadopulos & Associates, Inc, Bethesda-Marylan

A comparative study of the hydraulic parameters and the yield of wells of some sedimentary hard rocks of Albania

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A b s t r a c t : Short terms pumping tests of about 300 wells are used to study the hydraulic parameters and yield of wells of some conglomerate and sandstone aquifers outcropping in Periadriatic basin and in two inner sedimentary basins of Albania. For the purpose the frequency graphs for the transmissivity, coefficient of permeability and of specific capacity of wells were constructed. The calculations of transmissivity and of permeability were based on specific-capacity data of the wells. The investigated parameters of individual wells and their mean and median values have significant differences. The main evidenced sub-regional or local factors influencing the hydraulic parameters of the aquifers (and the yield of wells) are the petrology of rocks, their lithification degree, the solution of carbonate cement (of conglomerate aquifer), the structural position of wells as well as their geomorphologic position and the drilling technology.

INTRODUCTION

Albania is situated in the eastern coasts of Adriatic and Ionian Seas; Otranto Channel width about 80 km separates Albania from Italy. The territory of Albania is 28,749 km². Geologically it belongs to folded Alpine belt. The total outcropping area of hard rocks in Albania is about 20,000 km² (Eftimi *et al.* 1985). The country is divisible into internal and external zones. In both zones some important basins filled up by sedimentary molasses of different lithology are developed: Mati and Mokra sedimentary basins of internal zones and Periadriatic foredeep basin, the biggest one of the outer zones (fig.1). The objects of this investigation are: Low Neogene conglomerate and conglomerate-sandstone deposits of Mokra Basin; Upper Neogene (Tortonian) sandstone deposits of Mati Basin, Tortonian sandstone deposits and Pliocene conglomerate-sandstone deposits of Periadriatic basin known with the local name of Rrogozhina Formation. The total surface of the investigated area is about 4000 km².

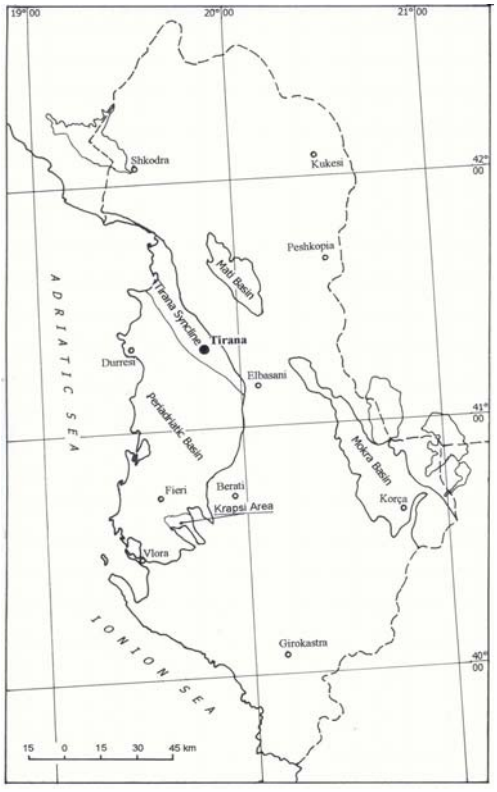

Figure 1. Location of investigated areas

THE INVESTIGATED PARAMETERS

The results of short-term pumping tests of about 300 drilled wells are used to estimate the transmissivity, T, coefficient of permeability, K, and the specific capacity of wells, q. For wells of equal diameter and equal efficiency, the specific capacity is directly proportional to the transmissivity of the aquifer. Even where the efficiency is variable, the specific capacity affords a reasonable good measure of transmissivity of the aquifer. As mentioned by Krásný (2002) the hydraulic conductivity in fissured rocks mostly represents a non-existing average permeability of the entire aquifer thickness.

The estimation of transmissivity is based on a modified version of the Thiem equation, which in a simplified version may be written as: $T=aq$, where $a=0.366\lg(R/r_o)$ and q is the specific capacity in $m^3/day/m$, R is the radius of influence at which the drawdown is zero and r_o is the nominal radius of the well. Specific capacity data adjusted for the total penetration (Kozeny 1933, Turcan 1963) and to a common radius and pumping period were used for the calculation of the transmissivity. The drawdowns at considered wells usually are less then 15% of the natural water head and the wells losses could be neglected (Gheorge 1978). The mean a-values for the wells of Rrogozhina formation resulted about 1.5 while for the wells of remaining investigated deposits resulted about 1.2. Dividing the transmissivity by the thickness of screened aquifer layers was found the coefficient of permeability.

The specific capacities decrease with the period of pumping because the drawdown continually increases with time as the cone of influence of well expands. For this reason the specific capacities of wells were computed for a pumping period, t=0.5 day and adjusted for a well radius, $r_o=0.054$ m. As aforementioned the correction is made also for partially penetrating wells.

RESULTS OF THE STUDY

For sandstone aquifer of Tirana Syncline and for Rrogozhina Formation aquifer, having a relatively large number of data, the distribution of statistical samples of transmissivity, permeability and of specific capacity is graphically represented on probability papers by the values of cumulative relative frequencies. For the other aquifers, having a limited number of data, only the corrected mean values of the same parameters are estimated. The results of the statistical treatment of data including the median values and the corrected mean values are summarised in tab.1 and 2. In the following the factors influencing on the magnitude of the hydraulic parameters as well as on the yield of wells are analysed.

Table 1. Characteristic values of T, K and q of wells of Low Neogene deposits of some sedimentary basins of Albania

Investigated area	Age of rocks	Lithology	Number of wells	Mean depth of wells, m	T, m²/d		K, m/d		q, l/s/m	
					50%	Mean	50%	Mean	50%	Mean
Tirana syncline, Periadriatic basin	Tortonian, Upper section	Thin bedded sandstone	46	267	2.5	3.1	0.067	0.09	0.025	0.03
Tirana syncline, Periadriatic basin	Tortonian, Lower section	Thick bedded sandstone	13	300	4.4	5.3	0.077	0.095	0.048	0.056
Periadriatic basin	Tortonian	Sandstone	10	189	-	5.2	-	0.23	-	0.05
Periadraitic basin, Kraps area	Tortonian	Friable sandstone	5	298	-	30.0	-	0.48	-	0.27
Mati basin	Tortonian	Clayey sandstone	6	176	-	4.5	-	0.15	-	0.04
Mokra basin	Aquitanian	Conglomerate and sandstone	6	194	-	14.0	-	0.25	-	0.12

Table 2. Characteristic values of T, K and q of wells of Pliocene deposits of Rrogozhina Formation

Area	Lithology	Number of wells	Mean depth of wells, m	T, m²/d		K, m/d		q, l/s/m	
				50%	Mean	50%	Mean	50%	Mean
Durres	Conglomerate and sandstone	33	211	110	134	2.5	4.0	0.85	0.95
Kavaja	Conglomerate and sandstone	46	189	40	69	1.25	2.56	0.33	0.55
Lushnja	Conglomerate and sandstone	24	145	39	78	1.55	2.96	0.31	0.57
Ardenica	Sandstone and conglomerate	25	159	26	45	1.15	2.09	0.21	0.36
Fier	Conglomerate and sandstone	58	209	66	97	1.70	3.00	0.50	0.75
Shushica	Sandstone and conglomerate	16	141	31	55	1.20	2.05	0.26	0.42
Total		212	177	54	80	1.52	2.74	0.42	0.61

As the investigated hard rocks are generally young, their hydrogeological parameters to a high degree are determined by the lithology (Krásný 2000). Referring to the data of tab.1 and 2 the values of hydraulic parameters of conglomerate rocks differ significantly from those of sandstone rocks; the transmissivity and permeability of conglomerate of Rrogozhina Formation are at least one order bigger then the values calculated for the sandstones. Essential differences of hydraulic parameters related to the lithology could be noticed also within the Rrogozhina Formation; the values of the investigated parameters resulted slightly higher in areas where the conglomerate rocks prevail over the sandstone rocks.

Within the same type of rocks very important factor determining the values of hydraulic parameters appear to be their lithification. Distinctly highest values of hydraulic parameters have the friable sandstone of Kraps area of Periadriatic basin (tab.1), which values are comparable with that of conglomerates. The lithification usually increases over geological time causing the decrease of the hydraulic parameters; the permeability and transmissivity of older conglomerate-sandstone rocks of Mokra basin (Aquitanian - Low Neogene), are in average more then five time smaller then that of younger Pliocene conglomerate-sandstone rocks of Rrogozhina Formation.

Relatively big differences have the spatial distribution of the hydraulic parameters and of yield of wells of Rrogozhina Formation. The permeability of conglomerate of Durres area is distinctly higher then in the remaining investigated areas (tab.2), though the petrographic composition, the degree of lithification and the fissuring of rocks is similar throughout the Periadriatic basin. The only reasonable explanation is related to the enlargement of fissures by the intensive solution of carbonate cement of conglomerate rocks, reminding on the karst processes. This phenomenon may be is more intensive in Durres area as the groundwater there is more mineralised. The chloride content in groundwater of Durres area is about 150 to 250 mg/L, while in the groundwater of the remaining areas of development of Rrogozhina Formation the chloride content varies from 25 to 50 mg/L.

Another important significant factor controlling the permeability of conglomerate-sandstone rocks of Rrogozhina Formation and of the yield of wells is their structural-tectonic position. It is observed that the transmissivity and the yield of wells located along the uprising sides of Divjaka and Ardenica anticline structures, which are accompanied by vertical rupture faults is usually 3 to 8 time smaller then the values of wells located at normally sloping flanks of the same structures.

In a local scale, the topographic and geomorphologic position of wells is the controlling factor of the transmissivity and of the yields of wells. Many drilling wells located in the centre of small valleys at foothills yield at least 2 to 3 times more water than the wells located at higher elevation slope areas.

The construction technology of wells is another important factor influencing on the calculated values of hydraulic parameters of rocks and on the yield of wells. The big diameter (in some places gravel pack) wells, abundantly screened and well developed by air compressed method, which are drilled during the last decade in Albania yield at least 2 to 3 times more water than the traditionally mud circulating rotary drilled small diameter wells.

It is concluded that statistical treatment of transmissivity data is the best method to characterise their spatial distribution and to predict with a good accuracy the yield of new wells in hard rocks.

REFERENCE

Eftimi R, Tafilaj I *et al.* (1985) Hydrogeological Map of Albania, scale 1:200,000

Gheorghe N (1978) Processing and synthesis of hydro-geological data. Abacus Press, Tunbridge Wells

Krásný J (2000) Geologic factors influencing spatial distribution of hardrock transmissivity. In O Sililo *at al.* (eds), Groundwater: Past achievements and future challenges, Proc. 30 IAH Congress, Cape Town, Balkema, Rotterdam:187-191

Krásný J (2002) Understanding hydrogeological environments as a prerequisite for predicting technogenic changes in groundwater systems. In K W F. Howard & R G Israfilov (eds) Current problems of hydrogeology in Urban areas. Urban Agglomerates and industrial centres, Kluwer Academic Publishers:381-398

Turcan AN Jr (1963) Estimating the specific capacity of a well. U.S. Geol. Survey Prof. Paper, 450-E, Washington

Hydraulic characterisation of the Uveghuta granite in Bataapati, Hungary

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A b s t r a c t : The Uveghuta site in Hungary is regarded as a potential location for the construction of an underground low and medium level nuclear waste repository. As part of the site characterisation phase numerous hydraulic measurements from deep boreholes were carried out. The present paper describes the general strategy and methodology used for conducting the measurements as well as preliminary results. Groundwater flow in granite can be best conceptualised as flow through a sparsely connected fracture network. As flow simulations through discrete fracture networks show, there are limits to our ability to characterise the hydraulic behaviour of such system in a deterministic way. It is therefore important to understand that an effective and realistic characterisation program can only follow stochastic criteria concerning fracture (i.e. transmissivity) distribution, head distribution as well as system connectivity. Given the fact that the system is highly unconstrained, understanding of the system behaviour cannot be demonstrated by creating a single model that is consistent with the field observations. In this case it is much more important to understand the range of possible model realisations that reproduce the measurements in an acceptable way. Simplification and conceptualisation become very important. Due to the highly heterogeneous nature of the rock, the spectrum of transmissivities encountered can encompass several orders of magnitude (e.g. from 1E-12 m^2/s to 1E-3 m^2/s). Therefore, the question of how we measure (i.e. methodology) becomes crucial. Here it is important to try to eliminate any bias related to the measurement method and recognise that the final goal of the measurement campaign is to get comparable results and not comparable measurements. The preliminary results of the hydraulic measurements at the Uveghuta site are presented in terms of transmissivity and head distribution profiles as well as flow path analysis and large-scale connectivity results.

Effect of depth on discontinuity aperture: the example of St. Aloisio mine (Northern Italy)

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A b s t r a c t : The results of rock mass discontinuity measurements taken at different depths in a multi-layer mine in Val Trompia (Brescia - Northern Italy) are reported. Investigation has been performed on a Scythian formation made up of limestones, sandstones, marls and siltstones. Outcrop surveys have been performed in the mine at four different depths. For each discontinuity the main parameters were identified. The relationship between the various parameters considered and the depth of the outcrop survey has been examined. Among the parameters investigated, aperture proved the parameter that shows the most significant variations with depth, decreasing as geostatic stress increases. These aperture variations obviously affect "effective fracture porosity" and the hydraulic conductivity of the rock mass, calculated on the basis of the cubic law. Further considerations on the relationship aperture-depth have been gained from the examination of the same relationship for the different discontinuity sets.

INTRODUCTION

Outcropping measurements of rock mass fracturing play an important role in hydraulic characterisation of fractured rocks. However, outcrop surveys are affected by the variation with depth of the geometric characteristics of the discontinuity net measurable on surface. Discontinuity aperture is without doubt one of the parameters of the rock fabric model drawn from outcrop surveys most liable to vary with depth (Lee and Farmer 1993). In actual fact the measurement of this parameter on surface is conditioned by rock weathering while hydraulic conductivity of the discontinuity system is extremely sensitive to the dimension of the aperture, taking into account the "cubic law" (Snow 1969)

This paper synthesises the results of the first phase of a wider research aimed at the comparison between hydrogeological features of the rock mass through outcrop surveys and direct tests on the aquifers. Specifically, the results of rock mass discontinuity measurements taken at different depths in St. Aloisio mine (Brescia - Northern Italy) are reported and discussed.

GEOLOGICAL AND HYDROGEOLOGICAL SETTINGS

St. Aloisio mine (790-720 m above s.l.) is located in Val Trompia, a valley cutting across sedimentary rocks of Prealpi Mountains, sited 100 km north-east of Milano (fig.1).

In this portion of Prealpi Mountains the sedimentary rocks of Upper Permian – Anisian overlie on pre-Westphalian metamorphic basement (fig.1). The sedimentary complex includes: conglomerates, sandstones and siltstones (Verrucano Lombardo Formation); limestone, sandstones, marls and siltstones (Servino Formation); dolostone, limestone and conglomerates (Carniola di Bovegno Formation); limestone (Calcare d'Angolo Formation). The complex tectonics of region strongly controls the valley that is characterised by thrusting, shearing and folding along two main directions, E-W and NNE-SSW oriented (Cassinis and Perrotti 1993).

The sedimentary complex makes up a low permeable aquifer (average yield approximately 0.012 $m^3/s \times km^2$), within which groundwater circulation involves the most fissured layers closest to surface (on average first hundreds meters). In the most heavily fractured zones near the faults groundwater flow is more active and at a greater depth. Groundwater outflows in the valleys, feeding rivers and numerous low discharge springs, and feeds aquifers of boundary plains.

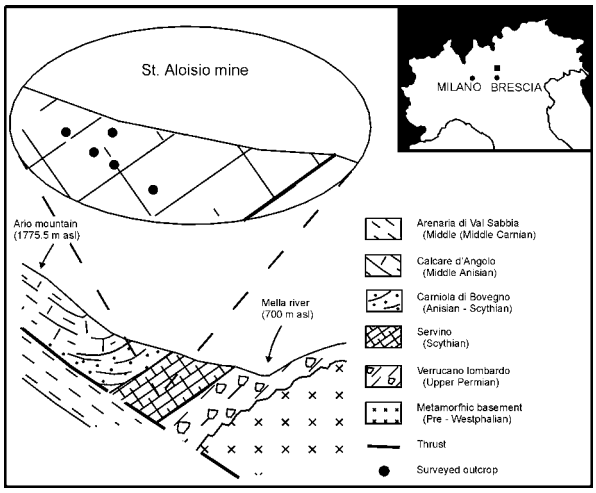

Figure 1. Location of the studied area and geological cross section

METHODS AND RESULTS

Investigations have been performed in St. Aloisio mine on Servino Formation. Locally limestone, sandstones, marls and siltstones beds dip towards S-SE. The mine penetrates the unsaturated zone of the sedimentary complex where groundwater flow occurs at a greater depth discharging in the River Mella.

Seven sites were examined in the mine at four different depths (fig.1). Outcrop surveys included detailed measurements of the discontinuity traces on rock mass (on a surface of at least 25 m^2).

Persistent discontinuities were represented by bedding joints and four fracture sets, mostly subvertical. The trend of the spacing of all discontinuity sets is bimodal with more frequent values between 10 and 50 cm. All aperture values are included in a reduced range (from 0.1 to 1.4 mm) with a modal frequency trend. Discontinuities generally are not filled. The roughness profile of bedding joints corresponds to JRC (Burton and Choubey 1977) range of 6-8, higher values have been found (JRC = 10-16) for fractures.

Among the parameters measured, aperture highlights the most significant variations with depth, decreasing as showed in fig.2. A low correlation between spacing and depth has been found (fig.3).

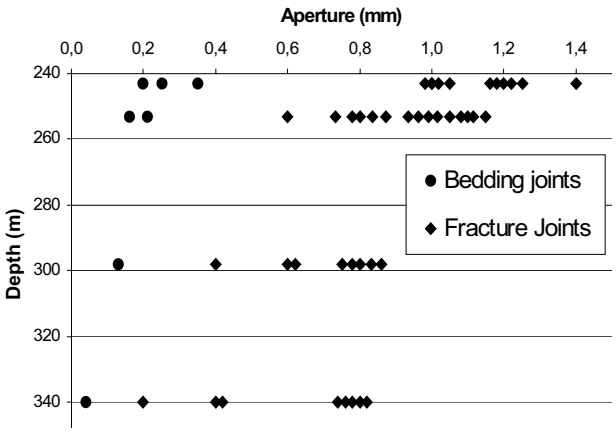

Figure 2. Variation of discontinuity aperture with depth

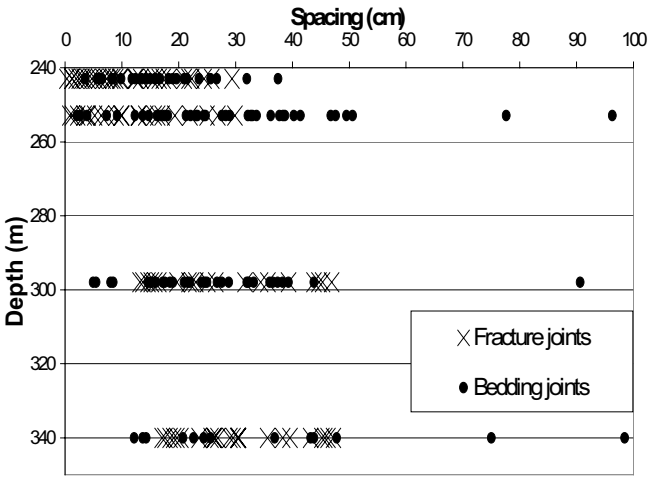

Figure 3. Variation of discontinuity spacing with depth

The in-situ state of stress along the investigated depth has been determined through two ways (ISRM 1997; Wareham and Skipp 1974). A first evaluation has been drawn from the determination of unit weight of rock specimens (from 21.83 and 24.12 kN/m^3) and considering the depth. A further assessment of in situ stresses has been carried out through the flat jack tests at two depths (234 and 340 m). The computed values of the vertical load agree with measured ones and vary in a reduced range (from 8.5 to 8.8 MPa).

CONCLUSIONS

Outcrop surveys provide a model of the rock mass characterised by a well-developed discontinuity net, a high frequency of discontinuities of the various sets and aperture values of generally less than 2 mm. The measurements also highlight that the aperture generally decreases with depth, though the mine excavation involved blasting.

These observed changes imply a decline in the effective discontinuity porosity and permeability of rock mass with depth. Hydraulic conductivity of rock mass computed on the basis of the cubic law (Wittke 1990) reduce from 10^{-3} m/s to 10^{-4} m/s for investigated depth (approximately 90 m). These values of hydraulic conductivity may not be considered in absolute terms but only in relative terms because of the lack of information about the true conducting aperture and connectivity of discontinuities. However, the decline of one order of magnitude of the hydraulic conductivity has good agreement with a regional groundwater flow occurring in the rock layers closest to surface. The different degree of closure with depth for the bedding joints and fractures (fig.2) may be linked to:

i) the orientation of the discontinuity planes with reference to vertical load,
ii) the different values of JRC between the bedding joints and fractures.

REFERENCES

Burton N, Choubey V (1977) The shear strength of rock joints, theory and practice Rock Mechanics 10:1-54

Cassinis G, Perrotti CR (1993) Interazione strutturale Permiana tra la linea delle Giudicarie ed i bacini di Collio, Tione e Tregiovo (Sudalpino centrale, N Italia). Boll Soc Geol Italiana 112:1021-1036

ISRM (1997) Proposte metodologiche per la determinazione dello stato di sollecitazione della roccia. Rivista Italiana di Geotecnica 01-03 1997

Cheng-Haw LEE, Ian FARMER (1993) Fluid flow in discontinuous rocks. Chapman and Hall

Snow DT (1969) Anisotropic permeability of fractured media. Water Resources Research 5/5:1273-1289

Wareham BF, Skipp VO (1974) The use of the flatjack installed in a saw cut in the measurement of in situ stress - Proc 3rd Int. Congr. On Rock Mechanics vol IIA:481-488

Wittke Walter (1990) Rock mechanics, Sprinter-Verlag

The influence of Cenozoic tectonics on the groundwater-production capacity and vulnerability of fractured rocks: a case study in Sao Paulo, Brazil

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INTRODUCTION

The focus of this investigation is the Metropolitan Region of Campinas, in the eastern part of the State of Sao Paulo, Brazil, an area that currently depends largely on fractured rocks for groundwater supply and where the industrialization and urban growth has been substantial in recent decades.

Based on a thorough lineament and structural analysis of this region, a new method, named HTD (Homogenous Tectonic Domain), was developed by Fernandes (1997), and published by Fernandes and Rudolph (2001), to determine the influence of late tectonics on the production of groundwater wells, drilled in low primary permeability rocks. The main method premise is that the most recent tectonics, in the study area, mostly controls the current aperture of fractures and, subsequently, the circulation of groundwater in fractured media.

The study area has undergone a long tectonic history since the Precambrian and, recently, it was affected by five strike-slip Cenozoic events, which probably generated sub-vertical extension fractures. The Cenozoic deformation is heterogeneously distributed and the method consists of determining the predominant event in selected areas, by means of a lineament analysis.

This approach pointed out that the most productive wells are associated with structures parallel to the maximum principal stress σ_1 of the dominant event in four of six analyzed areas. This suggests that the groundwater flow is locally greatly increased by the presence of extensional open fractures.

The HTD method contributes to groundwater resource development in fractured rocks once it provides a simple way of estimating where the most groundwater conductive fracture zones are. On the other hand, the same method can contribute for mapping the natural vulnerability of fractured aquifers, in a regional scale. A new method for this purpose, referred to as VULFRAC is described below.

THE MAPPING OF FRACTURED AQUIFER VULNERABILITY

The unique nature of the method here proposed, and referred to as VULFRAC, is principally due to the inclusion of the fracture analysis and the type of approach used for this purpose. The VULFRAC was applied to the eastern portion of the Metropolitan Region of Campinas that consists of Precambrian gneisses and granites. Fernandes (1997) and Fernandes and Amaral (2002) have recognized five brittle strike-slip Cenozoic events in the study area which, except the older one, affect the Rio Claro Formation. These events were named, from the oldest to the youngest, E1-NE, E2-EW, E3-NW, E4-NS and E5-NNE. The tectonic regime of all these events is strike-slip, and therefore, $\sigma 1$ and $\sigma 3$ are both horizontal to sub-horizontal. The direction of $\sigma 1$ is indicated as the compass position included in each event name. For instance, in the event E1-NE the $\sigma 1$ direction is NE-SW. They have generated mainly strike-slip faults, many times conjugate, whose deep exceeds about 70^{o}.

Premisses

A suitable starting point for the mapping of fractured aquifer vulnerability is the assumption that the flow of contaminants in the unsaturated zone may be controlled, to a large extent, by fractures, principally during recharge related to rainy periods or induced by the hydraulic surcharge associated with a polluting activity.

When the fractures are completely saturated, permeability in each one of them may be in the order of eight times greater than that in the matrix. Therefore, in near fully saturated conditions, fractures will control the flow (Wang and Narasimhan 1993). In more open fractures, the force of gravity will be more intense than the capillary forces and water will move more rapidly, possibly reaching the saturated zone.

It is considered that secondary permeability in the unsaturated zone is controlled by the density, connectivity and size of the aperture of fractures. With the objective of mapping these properties throughout the region, a joint analysis was made of lineaments, at the scale 1:100.000, and Cenozoic tectonic evolution in the area.

Method

The aquifer vulnerability was defined based on the interaction of three attributes of the unsaturated zone, namely: thickness and compositional nature of the material that comprises this zone (composition and texture), and the density, connectivity, and aperture of fractures at the site. The first two attributes govern the contaminant attenuation capacity of the unsaturated zone, whereas the last attribute controls the hydraulic accessibility of contaminants to the saturated zone.

In the study area the Cenozoic tectonics constitutes one of the principal phases of fracture generation and reactivation and, as is indicated by Fernandes and Rudolph (2001) it seems to have controlled the current aperture of fractures. In this way, a lineament map of the area (Fig.1) was subdivided in quadratic cells and an analysis of lineament trends through rose diagrams, elaborated for each cell, was performed in order to identify Cenozoic tectonic domains. Depending on the tectonic event that predominates in a given area, it can be assumed that a larger amount of extensional fractures can occur.

Besides, the whole lineament length and number of intersections was also achieved for each cell. It is considered that the density and connectivity of fractures are proportional to the density and intersection of lineaments. Based on these data, maps of tectonic domains and density and number of intersection of lineaments were elaborated.

The unsaturated zone in the region is composed mainly of the weathering products of Precambrian gneisses and granites. In view of the composition of the gneisses (peraluminous and intermediate to basic igneous composition), their weathering results in clayey materials, which have a greater contaminant attenuation capacity, when compared to the weathering products of the granites, which are sandy in texture. In this way the unsaturated zone was divided in two classes whose map correspond to the area of occurrence of granites and gneisses.

Finally, two classes of depth to water table were considered: lesser than or equal to 10m, and greater than 10m.

Results

The lineament analysis resulted in three maps: (1) total length of lineaments; (2) number of intersections of lineaments; and (3) tectonic-structural domains.

The map of tectonic-structural domains shows the presence of three sectors: (1) predominance of the E3-NW tectonic event; (2) predominance of the E4-NS event; and (3) transition areas

between the two. The event E3-NW is trans-extensional and is the most intense throughout the study region. It can be thus concluded that areas in which the E3-NW event predominates are those that most probably contain a larger number of extensional fractures and, therefore, with regard to fracture opening these would be the most vulnerable.

The combination of the three maps (total length and number of intersections of lineaments, and the map of tectonic-structural domains) resulted in three classes of fracturing:

- Class 1. Areas with low density and number of intersections of lineaments and a minor amount of open fractures. It is possible to observe that these factors coincide in area, a fact that greatly facilitates the mapping of classes of fracturing.
- Class 2. Areas with median density and number of intersections of lineaments, but with a greater amount of open fractures.
- Class 3. Areas with high density of lineaments, which mostly coincide with areas of a greater amount of intersections of lineaments, and also with areas that show the greatest number of open fractures (predominance of E3-NW event).

With respect to the class of fracturing, vulnerability increases as one goes from Class 1 to Class 3.

The three factors analyzed, namely, nature of the unsaturated zone, class of fracturing, and depth to water table, were cross-referenced through a matrix, resulting in the classes of relative vulnerability shown in tab.1. A map, with the resulting classes was produced on a scale of 1:100,000.

Table 1. Cross-referencing attribute matrix and classes of vulnerability

		Nature of the unsaturated zone (attenuation capacity)			
		Gneiss		Granite	
Fracturing intensity (hydraulic accessibility)	Class 1	L	MH	ML	MH
	Class 2	ML	H	MH	H
	Class 3	MH	H	H	
		>10m	<10m	>10m	<10m
		Depth to water table			

Vulnerability class abbreviation :

L Low; ML Moderate/Low; MH Moderate/High; H High

CONCLUSIONS

The joint analysis of lineaments and tectonic evolution has shown that the determination of Homogeneous Tectonic Domains is feasible for both large and small scales, namely, 1:25.000 and 1:100.000. The first scale is more suitable to recognize and map the more transmissive fracture zones. This application needs a precise tracing of lineaments, since it usually aims the sitting of wells. Scales smaller than 1:25.000, for example, 1:60.000, do not allow this accuracy.

On the other hand, scales around 1:100.000 are suitable for the drawing up of aquifer vulnerability maps, whose main applications are regulation of soil use and territorial planning. However, one should borne in mind that a Homogeneous Tectonic Domain determined at this scale, probably encompasses sub-domains of different tectonic events. In this way, for the selection of areas aiming the settling of a new contaminant activity, a more detailed analysis, regarding fractures and other attributes of the terrain, is required.

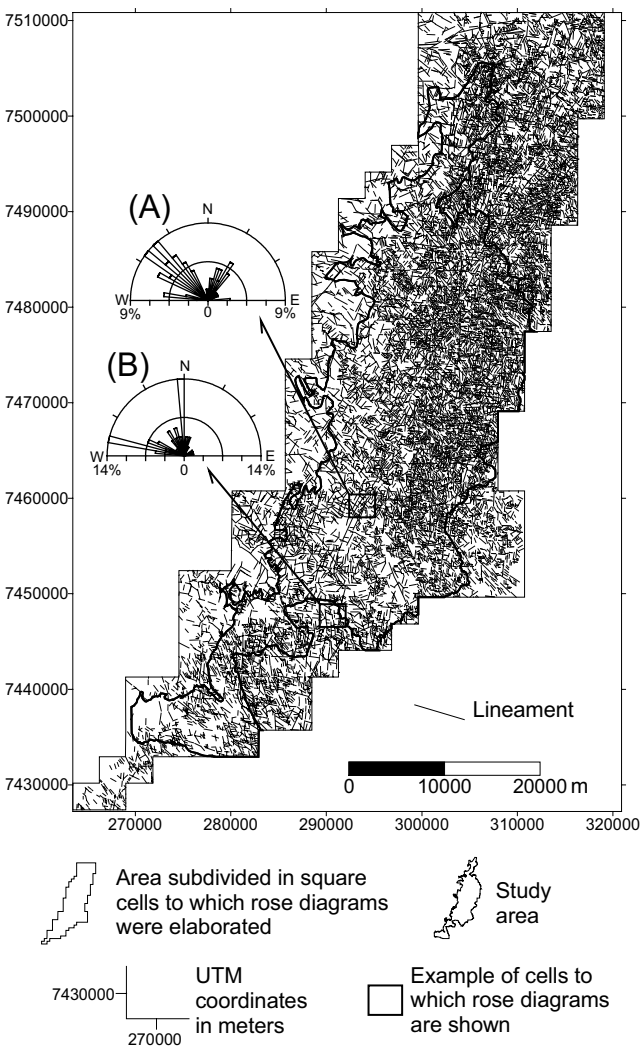

Figure 1. Map of lineaments elaborated through the interpretation of LANDSAT TM images (bands 4 and 5) at the scale of 1:100.000 (prepared by Fernandes 1997) and examples of cells with the respective rose diagrams

REFERENCES

Fernandes AJ (1997) Cenozoic Tectonics in the Middle Portion of the Piracicaba River Basin and its Application to the Hydrogeology of Fractured Media. PhD, University of Sao Paulo, Brazil (in Portuguese)

Fernandes AJ, Amaral G (2002) Cenozoic tectonic events at the border of the Paraná Basin, São Paulo, Brazil. Journal of South American Earth Sciences 14:911-931

Fernandes AJ, Rudolph D (2001) The influence of Cenozoic tectonics on the groundwater-production capacity of fractured rocks: a case study in São Paulo, Brazil. Hydrogeology Journal 92(2):151-167

Wang JSY, Narasimhan TN (1993) Unsaturated Flow in Fractured Porous Media. In: Bear J, Tsang C-F, de Marsily G (eds) Flow and contaminant transport in fractured rock. San Diego Academic Press:325-395.

Extraction of information about well characteristics of hardrock aquifers from GIS-based hydrogeological databases: example from Fennoscandia

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A b s t r a c t : Well data from ca. 13,600 boreholes in crystalline hard rocks in Fennoscandia from three profiles trending parallel to gradients of typical regional factors thought to be of importance for well yield and hydraulic properties have been analysed in a GIS environment and by statistical methods. Although recognized as important factors, the data analysis suggests that the effects of regional factors are more complex and probably of less importance than previously thought.

Important and relevant information about hardrock aquifers can be obtained from regional GIS-based hydrogeological databases. By using GIS-technology, large volumes of data required for regional hydrogeological studies can be generated by combining archive well-site data with information about geology, tectonics, hydrology, geomorphology, topography and regional stress fields.

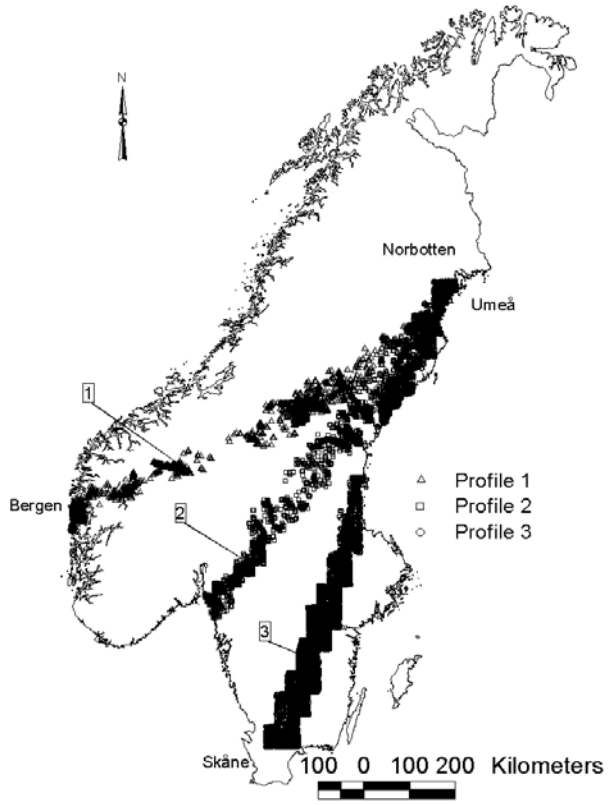

Figure 1. Map showing the Swedish-Norwegian part of Fennoscandia with selected hardrock wells in three profiles. The profiles run parallell with regional gradients of precipitation, net precipitation, runoff, annual rate of postglacial isostatic crustal uplift, and soil thickness

The obtained data can further be processed by statistical analyses. In statistical analysis, the data must often meet some requirements which, in case of hydrogeology and other sciences that explore distributions in nature, come into conflict with the ideal situation which makes use of all data. Hence, a dilemma in this type of exploratory data analyses of the hardrock environment is to ensure a representative collection of data from

In order to make a reliable statistical analysis from an initially large volume of data, quality-filtering techniques and the removal of outliers and extreme values as well as logarithmic transformation of the data may be necessary. The rejection of data to produce a high quality database may thus cause a considerable reduction in database records, and important information may get lost. Outlier data should therefore be dealt with explicitly.

In an analysis from the Fennoscandian crustal area the original dataset prior to filtering consisted of ca. 34000 records. Prior to the statistical analysis, the database was reduced to about 13,600 records. These groundwater hardrock wells were arranged in three profiles (Fig.1) oriented parallell to gradients of typical regional factors thought to be of importance for groundwater yield in hardrock wells from the Fennoscandian crust. The regional factors comprise annual rate of postglacial uplift and annual average precipitation, while soil type, soil depth and bedrock type are sub-regional and local factors.

There is no clear trend in well yield along the regional gradients. The typical regional variables; the rate of postglacial uplift and average annual precipitation, explain only a small portion of the total variation in well yield. However, the explanation power of these factors varies from profile to profile. It is considered that other, more local factors, such a proximity to fracture-correlated lineaments and topography may be of greater importance for well yield in this area. Also, some of the regional factors work in opposite directions along the gradients and may cancel each other out.

Finally, the results are discussed in light of the regional geologic, hydrologic and hydrogeologic framework. Additional developments of the database are also presented.

Lineament analysis in fractured rocks, methodology and application to the Suoimuoi karst catchment

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A b s t r a c t : Vast areas of the world consist of hard rocks (basement complexes), where water is restricted to secondary permeability, and thus to the fractures and the weathered zones. Most of such areas have a shortage of water. As the success ratio of drilling in hard rock terrain may be low, and the use of geophysics is often judged as too expensive, the study of lineaments from remote sensed imagery is an attractive alternative. High production areas in hard-rock aquifers are generally associated with conductive fracture zones. An effective method for defining the fracture zone is based on lineament indices, which are extracted from satellite imagery. Together with a detailed structural analysis and understanding of the tectonic evolution of a given area it provides a useful tool for hydrogeologists for studying groundwater in fractured rock and developing water resources.

The relationship of lineaments, fractures and groundwater is studied by Mabee *et al.* (1994), Kresic (1995), Sander (1997), Magowe (1999), Krishnamurthy *et al*. (2000). They agree that a high density of lineaments indicate in general the presence of groundwater. Hung *et al*. (2002) suggested that fractured rocks could be analysed by studying lineaments with the help of lineament indices. An application of the proposed methodology, on basis of Landsat ETM images, is given here for the tropical Suoimuoi karst catchment, NW-Vietnam.

LINEAMENT ANALYSIS

Lineaments are extracted from satellite images by edge enhancement functions available in most remote sensing software packages. The module GeoAnalyst, with the Line function of PCI Geomatica software is regarded to be one of the best functions for lineament extraction. However, its result is often still confusing and contains many errors from a geological point of view (Fig.1). Therefore, a correct image pre-extraction step is critical. Important aspects to consider in the preprocessing are the choice of bands, their spectral characteristics, image transformation or ratio methods and identification of zones with hydrological features. Taking the preprocessing into account will enhance lineament features and make them more appropriate for use in groundwater resources evaluation.

A necessary post-extraction step is the correction and analysis of the lineaments (Fig.2). In this article this step is performed by Lineament Analysis Software, which was developed by the Department of Remote Sensing and Geomatics of the Research Institute of Geology and Mineral Resources of Vietnam. In this software lineaments are corrected one or more times (removing, connecting…) based on the statistical and geological characteristics and the spatial scale of the lineaments.

Three main kinds of lineament indices for characterising a fracture zone are distinguished 1) Total length of lineaments - X, 2) Total number of lineaments - Y, and 3) Total number of lineament intersections - Z. At small-scale analysis the average length index can replace the above indices. The Lineament Analysis Software further takes into account the spatial distribution of the lineaments and provides tools for mapping and classifying lineaments.

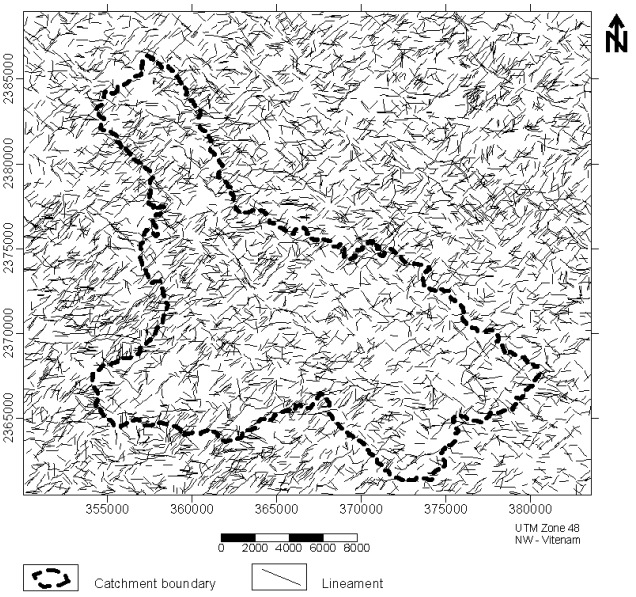

Figure 1. Lineament map of the Suoimuoi karst catchment resulting from PCI Geomatica extraction, no lineament analysis software was used

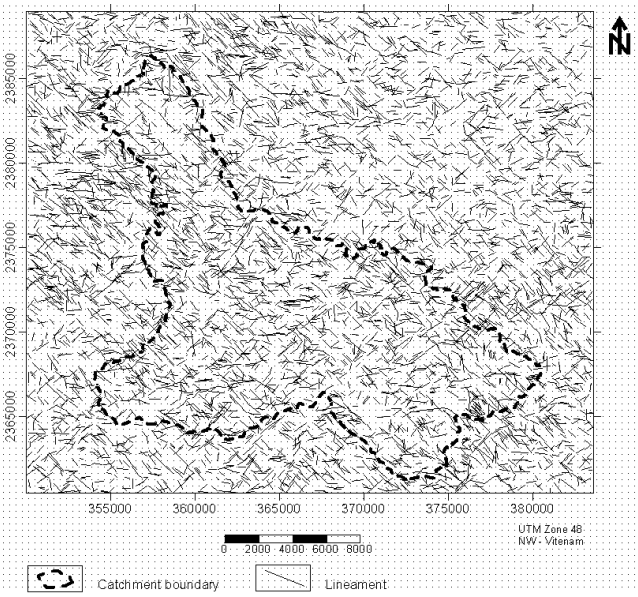

Figure 2. Map of lineaments, as given in Fig.1, postprocessed by lineament analysis correction software

FRACTURE ZONE CHARACTERIZATION

The fracture zone in the catchment is determined by local tectonic activities in the study area. Hop (1997) recognized major fault systems in NW-SE and E-W direction, they concluded that the fracture zone varies in width between 250 and 750 m around the NW-SE fault system.

The fracture zone is defined on basis of the density of a lineament index. The critical value of the lineament index for defining a fracture zone boundary can be estimated by field observations of the intensity of rock deformations. The hypothesis is that a higher lineament density index corresponds to a higher rock deformation. Facture zone (F) can be described as a function of the three lineament indices

$$F = f(X,Y,Z)$$

Two simple functions can be used for defining the fracture boundary by trial and error calibration based on the observations

$$F = aX + bY + cZ$$
$$F = X * Y * Z$$

where *a, b, c* are calibration constants. Fig.3 gives the resulting map of the lineament density function F.

The lineament software describes the fracture zones by their boundary, relative intensity, direction of lineaments and the conjugate pair of lineaments, which form the fracture zone (Fig.4).

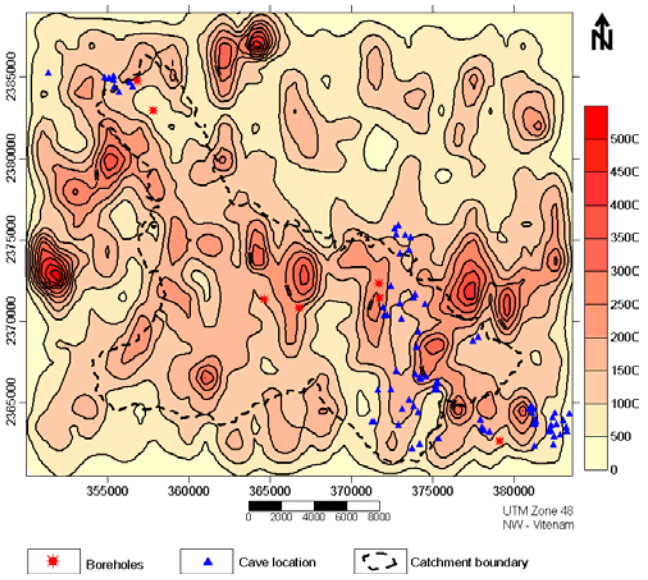

Figure 3. Map of lineament density function F

Bore--holes	Drilling depth	Thickness of overlying soil layer	Depth to static GW table	Pumping discharge
	DD (m)	ST (m)	SWT (m)	Q (L/s)
LK20	100	7.5	20.0	0.017
LK19	100	6.9	20.0	0.021
LK21	100	10.0	6.2	1.013
LK22	100	8.0	8.3	1.642
LK23	70	12.8	8.0	3.546
LK24	99	18.0	16.0	0.510
LK25	107	12.0	64.8	0.109

Table 1. Boreholes in the study area

The relationship between the identified fracture zone and the occurrence of groundwater is further improved by the results from pumping tests (Tab.1). The resulting lineament index density map can be correlated with the measured transmissivities in order to generate a groundwater transmissivity map.

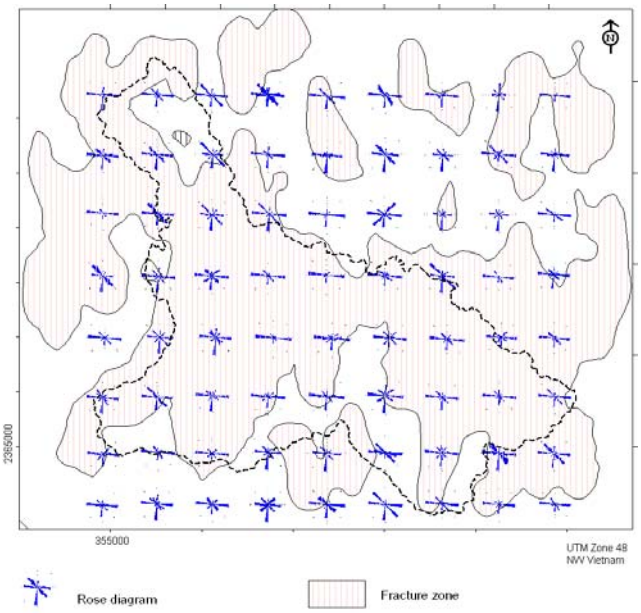

Figure 4. Map of delineated fracture zones

REFERENCES

Hop ND (1997) Geological map of Thuan Chau – Son La (Vietnam), Hanoi. The Geological Survey of Vietnam, 600 pp

Hung LQ, Dinh NQ, Batelaan O, Tam VT, Lagrou D (2002) Remote sensing and GIS-based analysis of cave development in the Suoimuoi catchment (Son La-NW Vietnam). Journal of Cave and Karst Studies 64(1):23-33

Krishnamurthy J, Mani A, Jayaraman V, Manivel M (2000) Groundwater resources development in hard rock terrain – an approach using remote sensing and GIS techniques. International journal of applied earth observation and geoinformation 2(3/4):204-215

Kresic N (1995) Remote sensing of tectonic fabric controlling groundwater flow in dinaric karst. Remote Sens Environ 53:85-90

Mabee SB, Hardcastle KC, Wise DU (1994) A method of collecting and analyzing lineaments for regional-scale fractured-bedrock aquifer studies. Ground Water 32(6):884-894

Magowe M, Carr JR (1999) Relationship between lineaments and ground water occurrence in Western Botswana. Ground Water 37(2):282-286

Sander P (1997) Water-well siting in hard-rock areas: Identifying promising targets using a probabilistic approach. Hydrogeol J 5(3):32-43

Sander P, Minor TB, Chesley MM (1997) Ground-water explorations based on lineament analysis and reproducibility tests. Ground Water 35(5):888-894

The Table Mountain Group of South Africa: a fissured aquifer of regional importance

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A b s t r a c t : The dominantly arenitic rocks of the Table Mountain Group of the Cape Provinces of South Africa, albeit having no primary porosity, were found to be good aquifers due to fracturing as a result of intensive faulting.

The Table Mountain Group (TMG) builds most of the Cape Provinces of the Republic of South Africa. It outcrops over an area of about 9,000 square kilometers, mostly mountainous, reaching elevations of 2000 m. The precipitation falling on the outcrops varies extremely. On its northern borders the climate is arid its annual precipitation does not exceed 200 mm, while in the southwestern region it may reach 2000 mm/y. Its total thickness is about 4000 meters (de Beer 2002) consisting of quartzitic sandstones of Ordovician to Silurian age. Because of the tectonic processes, which this region underwent since the Paleozoic Era the rocks are highly consolidated and of zero primary hydraulic conductivity, except for the few (to a few tens of meters) near the surface where relaxation and weathering processes brought to fracturing and fissuring.

During the mid seventies Issar on a visit to South Africa, as a guest of the Water Resources Commission of the South African Government, and on the basis of a visit thermal springs issuing along regional faults (temperatures reaching 65 ^{0}C), suggested that due the intensive faulting and fracturing, which might go into considerable depths enabling circulation of groundwater to these depths as depicted by the high temperature of the thermal springs. As a result of these considerations the TMG should be regarded as a regional aquifer and should be explored by deep drillings. However this suggestion was rejected by the official RSA water authorities and until the mid eighties only the most shallow zone was considered as aquiferous and worth drilling into. A few South African Hydrogeologists, however, ventured to suggest that the aquiferous properties of the TMG may extend to deeper depths (Weaver *et. al* 2002).

During the early 90's Issar was enabled to reassess his hypothesis during a series of visits to the RSA. This time on the invitation of E. Braune, Director Geohydrology of the Department of Water Affairs and Forestry (DWAF). An extensive survey, which included visits at the sites of hot springs and their location on the regional fault pattern, which could be followed on the satellite images, as well as results of the research on the chemical and isotopic composition of these springs by Mazor and Verhagen (1983) enabled the formulation of a more detailed conceptual model. Accordingly the TMG was suggested to consist of three interconnected zones of aquiferous fissured and fractured rocks, namely:

Zone 1. Local shallow systems of fissures related to the mechanical failure of the rocks, due to pressure release, and rock tension joints connected to local folds and faults. Zone 2. Regional deep systems of fissures and fractures, connected to regional faults caused by regional folding structures. Zone 3. Inter-regional systems of fractures connected with the inter-regional system of faults along the major tectonic lines dividing the TMS province into tectonic blocks.

The recharge of the aquifer is taking place into Zone 1 mainly in the high altitude regions where precipitation is maximal. From there it flows through and along the regional faults into Zone 2, from where it flows into Zone 3 and along the interregional faults. The outflows are from the fissures and fractures, as local perched springs in Zone 1., into riverbeds along the local and regional faults in Zone 2., and as hot springs or directly to the sea along the mega-faults of Zone 3.

In order to verify (or falsify) this conceptual model an extensive sampling of water from springs have been carried out and analyzed for its chemical and environmental isotopes composition. The sampling was carried out along transverses of the TMG province, starting from the sea and ending at high altitudes.

The results validated the conceptual model showing that indeed the water of some of the hot springs emerging at low altitudes have a depleted oxygen 18 and deuterium composition correlative to the water of the local perched springs sampled at high altitudes (Issar 1995). The influence of the altitude on the isotopic composition of the thermal springs was supported by the more extensive work on the thermal springs of the TMG by Harris and Diamond (2002).

In accordance with Issar's recommendations the DWAF adopted a long-term program of research, exploration and development of the TMG. One of the regions in which an intensive hydrogeological and hydrochemical research was carried out was the Klein Karoo province in the central part of the TMG belt (Kotze 2001). Simultaneously intensive investigation proceeded in other regions. This brought to many successes, the most convincing one was at Citrusdal in the Western Cape Province where a series of wells was drilled as a precaution against drought in case of a strong El Ninõ effect. Wells drilled to depths from 174 to 348 meters yielded quantities of 35 to 450 m^3/h. ^{18}O and ^{2}H analyses have shown that the composition becomes lighter with depth (Hartnady and Hay 2002), confirming Issar's conceptual model.

One of the main problems, which the quantitative stages of the hydrogeological research faced, was the determination of the hydraulic parameters of the aquifers. This due to the reason that the classical methods of deriving these parameters from pumping tests were based on the assumption of laminar flow in a porous homogenous media, while the TMG was not porous, not homogenous and the flow in the open fractures in the vicinity of the pumping wells could have become turbulent. Yet the various investigations have shown that on the average conventional pumping tests, coupled with other method of evaluation as analysis of spring flow, tests on dam foundations etc. do give a range of hydraulic coefficients, the average of which could be applied to calculate preliminary regional hydrological balances. This could give the order of magnitude of the volume of water flowing through a certain section and stored. Hydraulic conductivity coefficients (K) ranged from 1.99 m/d to 0.002 - 0.005 m/day. Transmissivity (T) values of a few hundred m^2/day characterized productive fractured zones. When it comes to storativity coefficients (S) the figure of 0.001 was found to be "a fair estimate for the bulk storativity of the Peninsula and Nardouw formations" (Rosewarne 2002), which are the two most arenitic and thus with the highest potential of being fractured and become aquiferous. On the basis of these values

Rosewane (op. cit.) estimated that there are a few tens of billions of cubic meters stored in the TMG aquifer.

Yet, in order to develop long-term aquifer management policies the next stage of the hydrogeological investigations must aim at the construction of computerized flow models. This stage should be promoted albeit the constraints, already discussed concerning determination of the hydraulic parameters. These constraints can be solved through trial and error procedures while calibrating the models to fit field data. This was the strategy adopted in Israel for the modeling of the flow in the limestone and dolomite karstic aquifers, which are also not homogenous.

REFERENCES

De Beer Ch (2002) The stratigraphy, Lithology and Structure of the Table Mountain Group. In: Pietersen K, Parsons R (eds) A Synthesis of the Hydrogeology of the Table Mountain Group – Formation of a Research Strategy. WRC Report No TT 158/01, Water Research Commission, Pretoria, R.S.A 9-18

Hartnady CJH, Hay ER (2002) Boshkloof Groundwater Discovery. In Pietersen and Parsons (eds) ditto, 168-177

Harris C, Diamond RE (2002) The Thermal Springs of the Table Mountain Group: A Stable Isotope Study. In: Pietersen, Parsons (eds) ditto, 230-235

Issar AS (1995) On the Regional Hydrogeology of South Africa. Unpublished Report no. 3. The Directotrate of Geohydrology DWAF SRA

Kotze JC (2001). Hydrogeology of the Table Mountain Sandstone Aquifer in the Little Karoo. Ph D Thesis University of Orange Free State Bloemfontein

Mazor E, Verhagen BT, Rosewarne P (2002) Hydrogeological Characteristics of the Table Mountain Group Aquifers In: Pietersen K, Parsons R (eds). etc. ditto, 33-44

Weaver JMC, Rosewarne P, Hartnady CJH, Hay ER (2002) Potential of Table Mountain Group Aquifers and Integration into Catchment Water Management. In Pietersen and Parsons (eds) etc. ditto, 239-240

The availability of groundwater in crystalline rocks of Kandy area, Sri Lanka

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A b s t r a c t : Hydrogeological investigation was carried out to obtain sufficient information on groundwater availability in the fractured metamorphic rocks in Kandy district of Sri Lanka. 47 boreholes were drilled with the average depth of 90 meters and 24 high yielding wells were selected and carried out long term pumping tests for each well using standard methods. Pump installation depth and dynamic water levels also calculated and the pumping time was limited for 16 hours per days allowing 8 hours for recovery. These groundwater supplies have been connected to the main public water supply and no serous problems have been recorded so far since the beginning for this project. This indicates that there are many hidden groundwater sources in hard rocky areas for future.

INTRODUCTION AND THE PROJECT

During the period of 1981-1990, which was declared as the International Decade for Water Supply and Sanitation, Sri Lanka, was able to launch several water supply and sanitation project for the benefit of rural people in the country. The donor of one such project is the Finnish International Development Agency (FINNIDA) with the object of providing safe drinking water and sanitation in the Kandy district. The project works were undertaken by SOIL AND WATER LIMITED, Finland in 1987. The projects involve planning and designing of water supply for the total area of Kandy district. The project supervision for Finland was done by FINNIDA and it was named as "Kandy District Water Supply and Sanitation Project (KDWSSP)". Hydrogeological investigations were carried out by this project for locating groundwater resources and determination of their properties for the realization of water supply in the area belonging to the Kandy district.

The objective of this paper is to determine hydrogeologically more favourable locations for high yielding deep wells which are to be used as sources for the proposed piped water supply scheme in the areas coming under Pathadumbra electorate of the Kandy district, Sri Lanka.

According to the project plan of the Kandy District Water supply and Sanitation project, the area of Kandy district has been divided into Assistant Government Agent (AGA) divisions, to carry out water resources studies including identification of communities, their requirements and areas to be implemented.

Pathadumbara AGA division, which is, situated north-east of Kandy district in the central hills of Sri Lanka is one of the priority areas belonging to the project. The project area is characterized by large and small river basins with ridge and valleys topography. The main road from Kandy to Matale is running through the area. The valleys and floodplains of the main rives and streams consist of belts alluvial lowlands. The project area covers nearly 46 square kilometres. The mean annual rainfall in the project area is about 1940mm. The average day temperature varies from 20^{o}C to 26^{o}C during the year. The humidity is relatively high and it is generally above 60%. The population of Pathadumbara AGA division is about 59,000 (in 1981 census) and the projected population for the year 2010 will be approximately 92,100.The estimated water demand for the project area is 10,000 cubic meters per day (SOIL AND WATER Ltd.,1990).

The deep wells have been categorized into hand pump borehole wells and production borehole wells. Hand pumps are installed for the low yielding wells (generally well yield is above 4 liters per minute) and electric water pumps are installed for production wells (very high yield above 100 L/min) for distribution of water through a distribution network, after pumping to a storage tank. In addition to the borehole wells large diameter shallow wells are recommended for some locations where accessibilities are poor.

General geology

In general, this area is underlain by typical Precambrian metamorphic rocks The major rock types in this area are biotite gneiss, hornblende biotite gneiss, charnockitic gneiss, quartzite, granulitic gneiss, garnet sillimanite gneiss and migmatitic gneiss. The structural settings and trend lines of the rocks in the project area exhibit a good morphotectonnic relationship to the topographical features. The strike of most of rocks shows 325^{o} direction and having deep dips ranging from 60-80^{o}. Two sets of major joints (lineaments) patterns exist in the area with strike directions 45^{o} and 135^{o}. Most of valleys are lying along the lineaments. The occurrence of groundwater in the project area is restricted to joint systems of which the density and the orientation vary according to the rock types and locality.

METHOD OF STUDY

Hydrogelogically favourable sites were initially located after a through interpretation of aerial photographs, satellite imageries, geological maps and the previous reports. The site locations were confirmed by field investigations, studying the geomorphological, geological and geostructural setting of the area. Geologically the areas where biotite gneiss, migmatitic gneiss and quartzite are underlain were selected because those are the highly fractured rocks in the investigated area. Deep groundwater may occur only under favourable structural conditions. Therefore rock contact zones, fractured zones and highly jointed places of the regional rocks were considered for site selections. The valleys lying along lineaments are the most suitable gemorphological condition for shallow and deep groundwater. Most of sites were selected within these valleys. The locations of springs within the region also considered as favourable sites.

Drilling : Based on the above investigation, 47 sites have been selected for deep drilling. The drilling operation have been conducted using DTH drilling rigs and compressed air. The diameters of boreholes were 115-200mm and the average depth was 90 meters. All boreholes were flushed and cleaned after the completion of drilling by compressed air and then flushing yield were measured. The deep wells have been categorized into hand pump borehole wells on the basis of flushing yields. All the wells in which the flushing yields were more than 100 liters per minute were selected as production wells.

Pumping Tests: Short and long term pumping tests were carried out for the selected production wells to study the characteristics of the aquifers. Short term pumping tests (step drawdown) were done to decide the suitable pumping rates and levels for long term pumping test. Finally the recovery was measured. After analysing the data of step drawdown test, the suitable pumping levels and rates were chosen for long term pumping tests. Then long term pumping tests were started for all the high yielding wells. The drawdown and water levels of all

wells including nearby shallow wells were measured with the time. All drawdown measurements were taken with respect to the ground surface. A standard method was used for carry out the tests (Helweg *et al.* 1982). All long term pumping test were carried out for nearly a period of one month and recovery measurement were recorded until the water level reach the original static water level. Some boreholes used as observation wells during pumping tests.

Analysis: Long-term pumping test data were analysed by using the Cooper-Jacob's equations. The drawdown of dynamic water level with time was used to calculate the transmissivity. The curves were drawn on normal and semi-log graph sheets respectively to understand the aquifer properties. The transmissivity higher than $10m^3$/day/m were selected as suitable wells for the proposed water supply scheme.

To calculate the amount to be pumped per day, the time of recovery period and the maximum drawdown of each well during the long term pumping period were carefully analysed.

The time-drawdown data indicated that water levels decrease about $1/3^{rd}$ of the maximum water level within the first hour of pumping in each well. Then at least six days take to reach the maximum drawdown or the constant dynamic water levels. The dynamic water levels after six days were fluctuating very slowly. Therefore any damage will not occur to the aquifer system from these pumping rates. This confirms the selected pumping rates from the initial step-drawdown tests are suitable for continuous pumping.

Generally the pump should be kept freely for some time for break the continuous pumping and maintenance proposes. If not it may reduce the pump efficiency and create some mechanical damages to the pump. Hence the pumping time and recovery time per day should be found from these data. The maximum time for groundwater pumping and minimum time for the recovery of the same water column per day was observed using the time-drawdown and time-recovery data for each well. As mentioned earlier, first hour of pumping reduce the water level of $1/3^{rd}$ of maximum drawdown and need a longer period to reach the same initial water level. But it is observed that the drawdown from 2^{nd} hour to 16^{th} hour of pumping could recover within 8 hours in most of wells. Therefore 16 hours pumping and 8 hour recovery per day can be recommended. Tab.1 show the recommendation of pumping capacity, pump installation depth and the dynamic water level for each well. The total maximum pumping capacity from all the wells were 8150 cubic meters per day. Using these rate, only 16 hour per day were recommended for the operation of water pumps and the rest of the time (8 hour) was allowed for recovery.

These groundwater supply scheme was began about 10 years ago. Those have been connected to the main public water supply scheme. Since then people of the area are using these resource for their domestic purposes. No serious problem or complains have been reported so far since the beginning of the project. Therefore this is a very good practical example for the occurrence of hidden groundwater resources in the hard crystalline rocky areas. However to use of this ground water for a longer period, those wells should be maintained properly.

CONCLUSION

This project was carried out to provide safe water for the people living in part of Kandy district. The investigations clearly indicate the occurrence of hidden groundwater sources in the fractured crystalline rocks and the amount to be extracted with a proper maintaining system for a continuous public water supply scheme. This amount may be not enough for the future with the increasing rate of population.

Table 1. Recommendation for each production well

Well No	Pumping capacity for 16 hours period m^3/day)*	Pump installation depth below ground level (m)*	Dynamic water level (m)
8005	1000	25	20
8006	1000	25	20
2112	200	45	35
2113	250	45	35
2114	275	45	35
2115	525	45	35
2118	300	45	35
2107	250	35	35
2108	500	35	35
2167	250	45	35
2169	250	45	35
2100	500	45	35
2120	500	45	35
2175	100	45	35
2135	200	45	35
2139	850	45	35
2140	300	45	35
2102	125	45	35
2123	200	45	35
2133	100	45	35
2134	125	45	35
2127	250	45	35
2125	100	45	35
* Recommended after the testing			

REFERENCES

Helweg OG, Scott VH, Scalmanini JC (1982) Improving well and pump efficiency. American water Works and Association, USA

Soil and Water Ltd (1990) Report on the study of groundwater resources in Pathadumbara AGA's Division in Kandy district. Kandy District Water Supply and Sanitation Project Report No. RI-80-00/41

A novel approach to the assessment of flow type in karst aquifers by evaluation of conventional test-pumping data

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A b s t r a c t : Groundwater flow conditions in karst aquifers fall in a continuous range between fully conduit and fully diffuse flow systems. Scrutiny of the literature on the subject of karst flow system characteristics reveals that previously developed techniques for assessing these characteristics of karst aquifers are applicable at the catchment scale only. Despite this gap in karst studies, determining the predominant groundwater flow type in karst aquifers at small scales is important for scientific and water resources management purposes such as groundwater vulnerability assessment. A new approach has been introduced which permits the estimation of the type of flow in karst aquifers using constant-rate pumping test analysis. In this approach, two parameters (*heterogeneity ratio* and *flow dimension*) are used to classify aquifer responses. These parameters have been used here as representatives of the degree of heterogeneity and the degree of interconnectivity of flow-conducting networks in karst aquifers, respectively.

INTRODUCTION

Studies concerning predominant flow types in karst aquifers have been undertaken for more than three decades (White and Schmidt 1966; Shuster and White 1971; Jacobson and Langmuir 1974 and so on). In most such studies, karst flow systems have been divided into two categories, i. e. diffuse–flow systems and conduit-flow systems. In diffuse flow systems groundwater moves through narrow-aperture fractures, joints and interconnected pores. Diffuse flow systems behave as porous aquifers because of the high degree of interconnectivity which exists between joints and pores. By contrast in conduit systems, groundwater moves through pipe-like conduits of large diameters (>1cm) and other large channels ranging in size up to caves.

Scrutiny of the literature regarding karst flow system characteristics reveals that previous studies have applied different approaches to the assessment of flow type at the catchment scale. There is no established approach suited to determining the predominant flow type at smaller scales, such as the scale of a borehole source – area.

The main purpose of this paper is to introduce a new method for identifying karst flow system type at scales much smaller than the catchment scale using conventional test-pumping data. This method relies on the use of two parameters i.e. the *heterogeneity ratio* and *flow dimension*. These parameters and their relationships with karst flow system characteristics will be examined in the following sections.

PUMPING TEST DERIVED PARAMETERS WHICH CAN BE USED FOR ASSESSING KARST FLOW TYPES

As was pointed out earlier, the main aim of this paper is to introduce a new approach for assessing flow type in karstic aquifers by evaluation of conventional pumping test data. The pertinent question that can be posed is ‘‘what sort of karst flow system characteristics can be reflected by pumping test data?’’

On the basis of karst flow systems characteristics mentioned above and pumping test information, it may be argued that just two characteristics of karst flow types can be assessed using pumping test data analysis:

1- The degree of heterogeneity, which is indicated by variations in time-drawdown data trends.

2-The degree of interconnectivity, which is reflected in flow geometry as revealed in the borehole pumping record.

These are the degree of heterogeneity and the degree of interconnectivity of flow-conducting features of karst aquifers, which appear as variations in hydraulic parameters during test and flow geometry conditions, respectively.

To quantify these two characteristics the *heterogeneity ratio* and *flow dimension can* be used, respectively. These parameters will be explained in the following sub-sections.

The heterogeneity ratio

In order to evaluate the degree of heterogeneity using pumping test data, a new method has been devised. In this method the variations of transmissivity at different pumping periods is quantified using a coefficient, which is called the heterogeneity ratio (Karami and Younger 2001). The heterogeneity ratio can be defined as follows:

$$H_R = \frac{\sum_{i=1}^{n} \left(\frac{\Delta_i + \Delta_{i+1}}{2} \times \Delta t_i \right)}{\sum_{i=1}^{n} \Delta t_i} \times 100$$

where

H_R = heterogeneity ratio

$\Delta_i = \left| 1 - T_i / \bar{T} \right|$

$\bar{T}$ = weighted average of values of transmissivity during a specific interval of pumping test

T_i = transmissivity determined from i_{th} period of pumping test, all periods start at t = 10min and end at $i(\Delta t_i)$

Δt_i = time interval between each of *n* successive pumping periods

The results obtained from different sites with different transmissivities, pumping test periods, and pumping rates reveal that values of heterogeneity ratio range between 0% and as much as 19%. It should be noted that the heterogeneity ratio does not depend on the absolute transmissivity of the karstic aquifer, but depends only on the variations of transmissivity in that section of a karstic aquifer which is affected by a given pumping test. Therefore, it may be concluded that if heterogeneity and flow geometry can be quantified for any pumping test, they can serve to estimate the flow type in the aquifers.

The flow dimension

Recent studies regarding the hydrogeological characteristics of fractured rocks have used a novel and simple technique to derive flow geometry from well tests. This technique uses the concept of flow dimension (Barker 1988). The flow dimension concept is

based on the idea that the flow volume in a fracture system (V) or flow area (A) could grow as an integral or a non-integral power of distance from the borehole (r).

Barker (1988) stated that, for transient flow conditions, the value of flow dimension is less than or equal to two and it can be directly calculated from the slope of a plot of the logarithm of head against the logarithm of time (for large times). Chakrabarty (1994) took up this idea for determining the value of flow dimension under transient flow conditions. In this approach, the values of head against time on log-log plot would give a slope of N, and the flow dimension (D_f) can be calculated using D_f = 2 – 2N.

ASSESSING THE AQUIFER FLOW TYPE AT PUMPING-TEST SCALE

On the basis of the flow dimension concept and karst flow system characteristics, it is to be expected that the greater the values of flow dimension, the greater is the contribution of diffuse flow and *vice versa*. Furthermore, according to the degree of heterogeneity and karst flow systems characteristics, it may be argued that the greater the heterogeneity ratio, the greater is the contribution of conduit flow. Based on such a logic, karst flow systems can be classified by conjointly using flow dimension and the heterogeneity ratio.

In applying such a method for classifying karst flow systems, specifying the lower and upper limits of both flow dimension and heterogeneity ratio is a prerequisite. As the most likely flow dimension falls between one and two. Therefore, the lower and upper limits of flow dimension are selected as one and two, respectively. This specified range has been divided into four categories for use in karst flow system classification (Tab.1).

With regard to the heterogeneity ratio, the lower limit undoubtedly is 0 % (for hydraulically homogeneous aquifers). Obtained values of heterogeneity ratio for various pumping tests using different methods (Theis, Cooper-Jacob and Moench) have yielded values ranging between 0 % and as much as 19 %. Considering the obtained values and the corresponding pumping test data characteristics (e.g. variations of the slopes in semi-log plots), it seems likely that heterogeneous karst aquifers will exhibit H_r values in the range 10 % to 20 %. Values in excess of 20% are likely only in the most highly heterogeneous karst aquifers. Similarly to flow dimension values, this relatively narrow range of H_R values has been sub-divided into four categories that will be applied in karst flow systems classification (Tab.1).

Finally, based on categorising the flow dimension and heterogeneity ratio, a graphical classification has been introduced for estimating karst flow systems (Fig.1).

Table 1. Proposed categorisation of aquifers using the heterogeneity ratio and flow dimension

Heterogeneity Ratio (H_r)		**Flow Dimension (D_f)**	
Values of H_r (%)	Degree of Heterogeneity	Values of D_f	Degree of Interconnectivity
Less than 5	Low	1.00 – 1.25	Low
5 – 10	Medium	1.25 – 1.50	Medium
10 – 15	High	1.50 – 1.75	High
Over 15	Very High	1.75 – 2.00	Very High

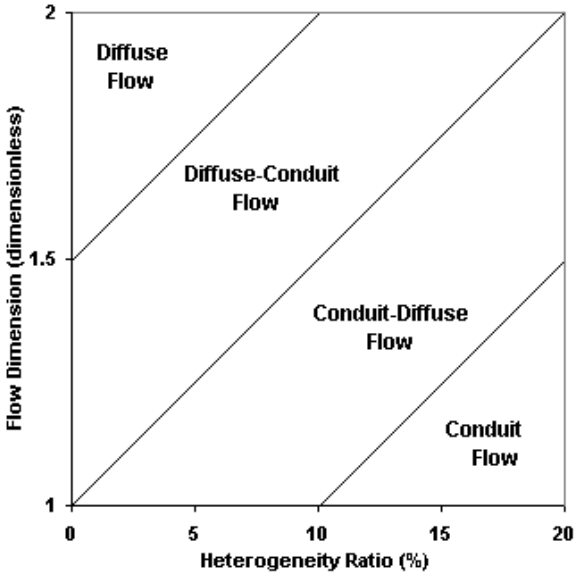

Figure 1. Proposed classification of karst flow systems

CONCLUSION

It may be claimed that previous techniques for classifying flow types in karst aquifers have only been applicable at the catchment scale. Therefore, there is no technique to determine the predominant flow type at smaller scales of engineering interest. The main purpose of this paper was to introduce a new technique for identifying karst flow system type at scales much smaller than the catchment scale using conventional pumping test data. This new technique is based on karst flow systems characteristics, which are reflected in pumping test data. These are the degree of heterogeneity and the degree of interconnectivity of flow-conducting networks of karst aquifers. To evaluate these parameters, heterogeneity ratio (which has been devised in this research) and flow dimension (which has recently been used for characterising fractured rocks) are applied, respectively.

REFERENCES

Barker JA (1988) A generalized radial flow model for hydraulic tests in fractured rocks. Water Resour Res 24(10):1796-1804

Chakrabarty C (1994) A note on fractional dimension analysis of constant rate interference tests. Water Resour Res 30(7):2339-2341

Jacobson RL, Langmuir D (1974) Controls on the quality variations of some carbonate spring waters. J Hydrol 23:247–265

Karami GH, Younger PL (2001) Analysis of test-pumping data in karst aquifers. In: Proceedings of the 7th Conference on Limestone Hydrology and Fissured Media, 20-22 September 2001, Besancon, France, pp 195-198

Shuster ET, White WB (1971) Seasonal fluctuations in the chemistry of limestone springs: A possible means for characterising carbonate aquifers. J Hydrol 14:93–128

White WB, Schmidt VA (1966) Hydrology of karst area in East – Central West Virginia. Water Resour Res 2:549–560

Vertical anisotropy of hydraulic conductivity in hard-rock aquifers

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A b s t r a c t : Pumping tests carried out in the fractured horizon of a granitic hard-rock aquifer, interpreted at the observation wells by means of the analytical solution of Neuman and at the pumping wells using that one of Gringarten show the vertical anisotropy of this layer of the aquifer; the horizontal permeability being clearly and systematically higher than the vertical permeability. These results perfectly agree with the geological observations, the fractured layer of the weathered granite profile showing the existence of many sub-horizontal fractures. It confirms dominating role, within the fractured layer, of the permeability of fractures due to the weathering process over that one of fractures with a tectonic origin.

INTRODUCTION

The Maheshwaram watershed located 30 kilometres away from Hyderabad in India is the main study area of the Indo-French Centre for Groundwater Research (French Geological Survey / National Geophysical Research Institute). Granites constitute the whole basin and the weathering profiles are easily observable through many dug wells used by the farmers for irrigation. The hydrogeological characteristics (e.g., hydraulic conductivity and storage) of the weathered mantle and underlying bedrock derive primarily from the geomorphologic processes of deep weathering and stripping. The classical weathering profile comprises the following layers, which have specific hydrodynamic properties, from the top to the bottom: (a) unconsolidated weathered mantle (regolith) issued from prolonged in situ decomposition of bedrock. This complex unconsolidated layer has a high porosity and a low permeability. (b) fractured zone is constituted by fractured-weathered hard rock, with generally a depth-decreasing density of fractures. These fractures could be caused by cooling stresses in the magma, subsequent tectonic activity or lithostatic decompression processes. Recent works (Wyns *et al.* 2002) demonstrated that they could also result from the weathering process itself. This layer assumes the transmissive function in the aquifer and is pumped by most of the wells drilled in hard-rock areas. (c) fresh basement is permeable only locally, where tectonic fractures are present. In the study area, under a few decimetres of red soils, the regolith with a thickness of 0 to 5 meters covers the fractured horizon. A high density of horizontal fractures is observed in the fractured horizon (fig.1). Vertical fractures with a tectonic origin are also present. Due to the overexploitation of groundwater resources, water levels are far below ground level and the alterites are dry while only the fractured zone is saturated. This allows us to test specifically this layer through pumping tests.

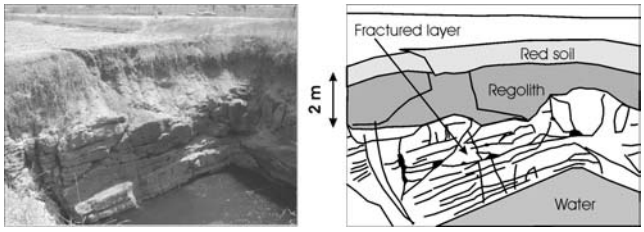

Figure 1. (a) Photography of a Dugwell in the Maheshwaram Area. (b) Identification of Various Layers, Horizontal Fractures and Diaclases

NEUMAN METHOD AT OBSERVATION WELLS

On a bi-logarithmic diagram (fig.2), the drawdown curves at observation wells IFP-1/1 and IFP-1/2 during pumping tests at IFP-1 well have a complex shape, difficult to interpret with classical methods (Theis for example, even considering an impermeable boundary). Drawdown curves are composed by three parts: the first one, at short times, with strong slopes, is followed by an intermediate period during which a level stabilisation occurs; a third part for long times shows a new increase of slopes.

The theory initially developed by Boulton and Pontin (1971) to interpret some special curves obtained in the observation wells takes into account the notion of « delayed yield from storage in unconfined aquifers ». It was improved by Neuman (1975) who developed an analytical solution adapted to anisotropic unconfined aquifers where K_r is the radial permeability parallel to the aquifer extension and K_z is the vertical permeability. Neuman considers an unconfined and infinite aquifer. When a constant discharge rate is pumped in a complete well, the water comes for one part from the storage in the aquifer and for the other part from gravitational drainage at the free surface. The Neuman solution, under abacus, gives reduced drawdowns in an observation well located at a radial distance r from the pumping well, as a function of reduced time for type A curves and reduced time for type B curves. The application of this method consists in matching the observed drawdowns on the abacus constituted by both types of curves: type A curve for short times and type B curve for late times (fig.2). Both curves are characterised by the same parameter $\beta=r^2K_D/b^2$ which is a function of the permeability anisotropy $K_D=K_z/K_r$, the thickness of the aquifer b and the distance r between the observation and pumping wells.

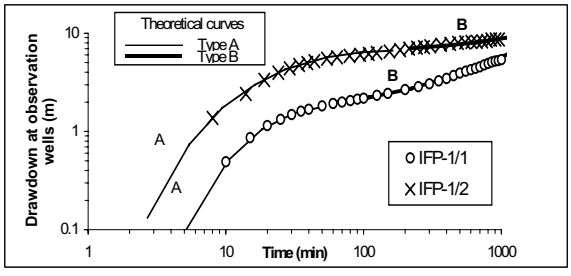

Figure 2. Adjustment of Drawdown in Observation Wells IFP-1/1 and IFP-1/2 using Neuman Theoretical Curves of Types A and B

The application of this method (tab.1) to the observation wells IFP-1/1, IFP-1/2 and IFP-9/1 leads to the evaluation of transmissivities, storage coefficients (*S*) and specific yields (*Sy*). Very similar values obtained in each observation wells for T_A and T_B show the coherence of the interpretation of this pumping test using Neuman method. The values obtained for specific yields are consistent with other ones deduced from water levels fluctuations using a global model (Engerrand 2002).

Table 1. Transmissivity and Storage Parameters Obtained by Adjustment of Drawdown (T_A : Transmissivity Obtained by Adjustment on Type A Curve, T_B : Transmissivity Obtained by Adjustment on Type B Curve, T_{AB} : Average of T_A and T_B)

Observation well	T_A/T_B (-)	T_{AB} (m^2/s)	*S* (-)	*Sy* (-)
IFP-1/1	0.90	1.86E-05	7.0E-05	1.7E-03
IFP-1/2	0.97	1.74E-05	3.7E-05	1.5E-03
IFP-9/1	0.73	6.51E-04	7.1E-04	3.4E-03

The determination of K_D needs the knowledge of the aquifer thickness *b*. Flowmeter measurements during injection tests in eight wells of the basin have shown that the fresh basement does not contain any conductive fracture. It is namely the case in pumping wells IFP-1 and IFP-9. Thus, the top of this layer was chosen as the bottom of the aquifer. As for classical methods, the uncertainty on the value of *r* makes difficult any interpretation of drawdown in pumping wells. The results of the interpretation at observation wells, included in tab.2, show an anisotropy of the permeability tensor, in accordance with geological observations: horizontal permeability is systematically higher than vertical one. This result is consistent with the observation of many horizontal fractures in dug wells.

Table 2. Permeability and anisotropy degree determined at observation wells using Neuman method

Observation well	β (-)	K_r (m/s)	K_Z (m/s)	K_D (-)
IFP-1/1	1.00	8.5E-07	5.2E-07	0.606
IFP-1/2	0.20	8.0E-07	1.0E-07	0.126
IFP-9/1	0.60	9.0E-05	3.0E-06	0.034

GRINGARTEN METHOD AT PUMPING WELLS

Flowmeter vertical profiles in IFP-1 and IFP-9 have shown that a few fracture are conductive, respectively three and one. Actually, at IFP-1, only the deepest fracture was saturated during the whole pumping test, quadratic head losses estimate confirming this finding. Similarly, the only conductive fracture intersected by IFP-9 was also saturated during the whole pumping test. Moreover, the analysis by Neuman method arises the existence of hydraulic anisotropy due to the presence of horizontal fractures. Thus, the method developed by Gringarten and Ramey (1974) for a vertical well intersecting a horizontal fracture in an anisotropic aquifer, applicable to the pumping well, is well adapted to the hydrogeological context of IFP-1 and IFP-9 wells.

The complexity of the analytical solution necessitates an interpretation through the adjustment of observed drawdowns on theoretical curves of an abacus (Gringarten and Witherspoon 1972) giving the reduced drawdowns in a pumping well as a function of reduced time for various geometrical configurations represented by the parameter H_{DG}, when the fracture is located at the centre of the aquifer, where z_f is the distance between the fracture and the bottom of the aquifer, *H* the aquifer thickness. K_r, the permeability along the radial direction parallel to the fracture, can be interpreted as the permeability increased by the existence of the horizontal fracture. K_z, the vertical permeability, represents the block permeability, *Ss* the specific storage coefficient, *t* the time since the pumping starting, r_f the radius of the horizontal fracture, *s* the drawdown and *Q* the pumping discharge rate.

Adjustments of observed drawdowns by Gringarten theoretical curves lead to high values of H_{DG}, suggesting a high permeability anisotropy. Knowing the geometry of the case (i.e. the thickness *H* of the aquifer), supposing the distance z_f between the bottom of the aquifer and the fracture equal to 0.5**H* and reusing the value determined previously by Neuman method for the anisotropy ratio (average of 4.8 at IFP-1/1 and IFP-1/2 and 29.5 at IFP-9), the hydrodynamic properties of the only conductive fracture are evaluated (tab.3). The total extensions of the intersected fractures are 32 and 8 meters at IFP 1 and IFP 9 respectively, coherent with field observations on near outcrops. It is observed that the anisotropy of the aquifer is also shown in the pumping wells using this method.

Table 3. Permeability, anisotropy degree and radius of the horizontal fracture determined at pumping wells using Gringarten method

Pumping Well	z_f m	z_f/H	H_{DG}	r_f m	K_r m/s	K_z m/s	K_r/K_z
IFP-1	6.0	0.28	3	15.9	3.4E-6	7.1E-7	4.8
IFP-9	4.0	0.55	10	4.0	5.7E-5	1.9E-6	29.6

CONCLUSION

The geological observations done on the granites of the Maheshwaram watershed (India) confirm the existence, as in many other areas of the World, of a high density of horizontal fractures in the fractured zone of the weathering profile. Measurements done using flowmeter confirm that only a few of these fractures are conductive. The interpretation of pumping tests on several wells with observation wells shows systematically the existence of a vertical anisotropy of permeability: the horizontal permeability is 2 to 30 times higher than vertical permeability. These results confirm the major role of weathering-origin fractures on the hydraulic parameters of hard-rock aquifers, tectonic-origin fractures having a less important role. The application of Gringarten theory also allows determining the radius of horizontal fractures crossing the pumping wells.

REFERENCES

Boulton NS, Pontin JMA (1971) An extended theory of delayed yield from storage applied to pumping tests in unconfined anisotropic aquifers. J Hydrol 14:53-65

Engerrand C (2002) Hydrogéologie des socles cristallins fissures a fort recouvrement d'altérites en régime de mousson : étude hydrogéologique de deux bassins versants situés en Andhra-Pradesh (Inde). PhD Thesis University Paris VI

Gringarten AC, Witherspoon PA (1972) A method of analysing pump test data from fractured aquifers, In: Mechan IAoR (ed.), Percolation through fissured rock. Deutsche Gesellschaft fur Red and Grundbau, Stuttgart: T3B1-T3B8

Gringarten AC, Ramey HJ (1974) Unsteady-state pressure distribution created by a well with a single horizontal fracture, partially penetrating or restricted entry. Trans Am Inst Min Eng 257:413-426

Neuman SP (1975) Analysis of pumping test data from anisotropic unconfined aquifers considering delayed gravity response. Water Resources Research 11/2:329-342

Wyns R, Baltassat JM, Lachassagne P, Legchenko A, Vairon J, Mathieu F (2002) Application of Magnetic Resonance Soundings to Groundwater Reserves Mapping in Weathered Basement Rocks (Brittany, France). Bull Soc géol France, to be published

Flux-induced solution weathering in a large displacement fault damage zone

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A b s t r a c t : The Hurricane Fault is a major intraplate boundary separating the Colorado Plateau from the highly extended Basin and Range physiographic province in southern Utah, USA. Near Hurricane Utah, where the fault zone is well exposed in the Virgin River Canyon, 250 L/s of elevated TDS (≈ 10,000 mg/L), thermal (≈ 40 °C) groundwater discharges from a 600 m wide damage zone exposed in the canyon. Copious CO_2 gas also discharges. Groundwater discharges are concentrated in 3 regions in the damage zone with increasing discharges away from the fault core. The largest discharge region issues near the intersection of a regional orthogonal fracture set. Groundwater issues from solution-weathered fractures oriented approximately parallel to the fault (0 to 20^o E) and the density of across bedding fractures decreases with distance from the fault. We attribute the relationship between decreased fracture density and increased groundwater discharge to flux-induced solution weathering.

GEOLOGIC AND HYDROLOGIC CONDITIONS

The active Hurricane Fault has ≈1000 m of vertical displacement (Stewart *et al* 1997). The Virgin River Canyon trends approximately normal to the fault strike (Fig.1). All groundwater discharges from highly fractured, horizontally bedded limestone, siltstone, and sandstone in the footwall (Fig.1). Groundwater does not issue from fault gouge zone or bedrock in the hanging wall. The cross-section in Fig.1 approximately parallels the river channel. Although the Virgin River at this location is entrenched due to uplift of the Colorado Plateau margin and/or reduction in base level, stream patterns do not reflect simple channelized meanders (Fig.2). This suggests that during downcutting, the stream has exploited nearly orthogonal fracture systems at about ~N25°E and ~N65°W.

Copious CO_2 gas discharges occur in 4 regions, three of which are associated with significant groundwater inflows (Fig.3). A major area of gas inflow at about 425 m is not associated with appreciable water inflow. Groundwater primarily discharges in and slightly above the river bottom and is concentrated in 3 regions in the damage zone. Discharge rates are greatest away from the fault core but still in the damage zone (Fig.4). Distances from the fault and discharge rate increases are approximately 50 m (60 L/s), 275-375 m (125 L/s), and 460-500 m (65 L/s). No groundwater inflow occurs beyond 550 m from the fault core.

Groundwater issues from solution-weathered fractures oriented approximately parallel to the fault (0 to 20^o E) and the density of across bedding fractures decreases with distance from the fault. Near the fault, across bedding fracture, with lengths greater than 10 m, have an average density of ≈ 0.4 m^{-1}. Although the overall density decreases to ≈ 0.2 m^{-1} where inflow rates are greatest, there is an increase in the number of very long across bedding fractures.

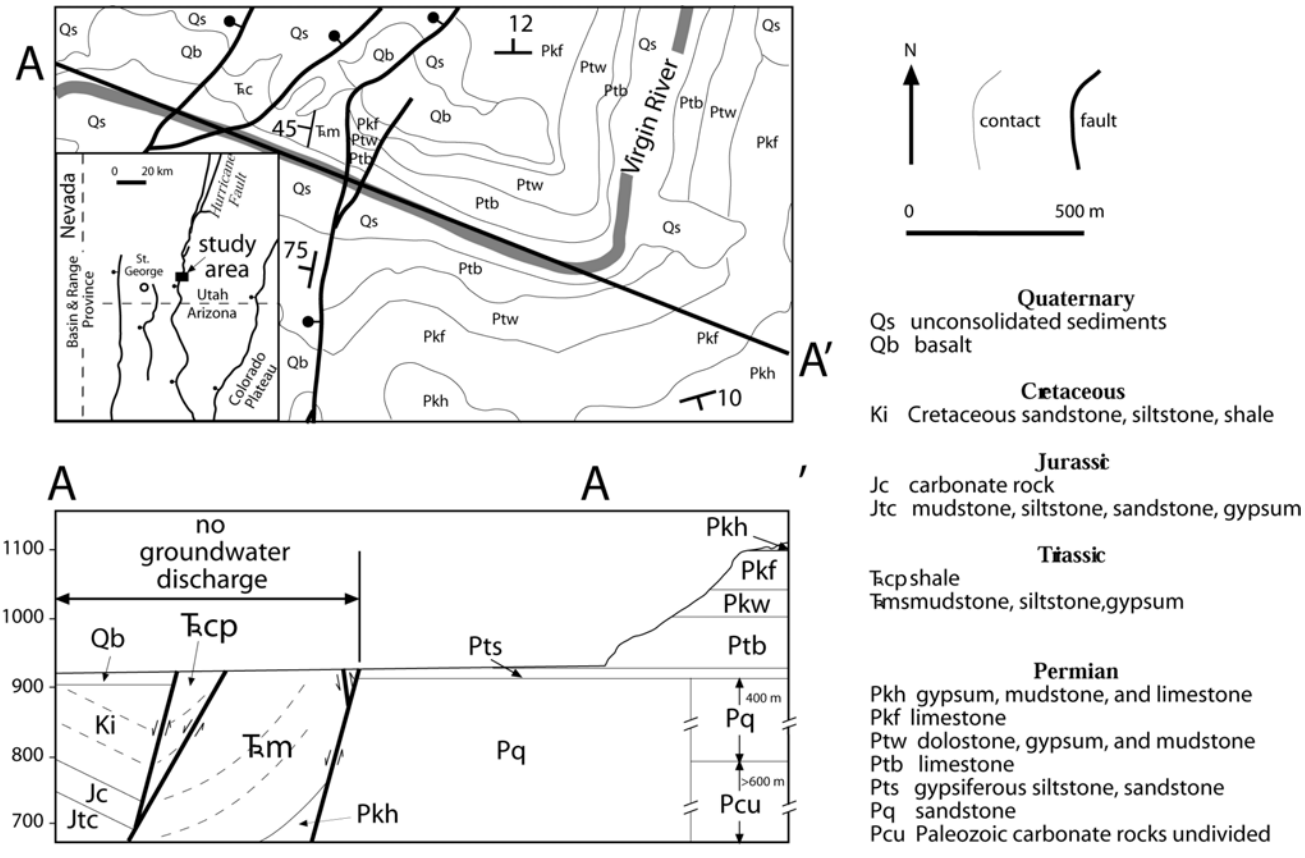

Figure 1. Geologic map and cross-section (geologic map modified after Biek, 1998)

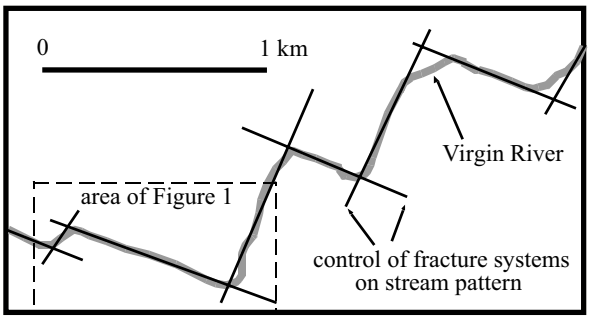

Figure 2. Map of large scale Virgin River fracture patterns

DISCUSSION

The greatest intensity of CO_2 gas vents and the largest flux of groundwater inflows occur at the intersection of the orthogonal fracture system about 300 - 400 m from the fault. We suggest that the discretization of groundwater discharges to the stream is controlled by such fracture systems. In particular, northeast oriented fractures and fracture zones are likely to be open, as they are perpendicular to the regional direction of extension. These same fractures are likely to be preferentially transmissive because fracture permeability scales proportionally to the cube of fracture aperture.

We attribute the relationship between decreased fracture density and increased groundwater and CO_2 gas discharge to flux-induced solution weathering. Beneath the carbonate sequence, deeper in the damage zone, the hydrodynamic pressure is relatively uniform across the damage zone. Where the fracture density is greatest in the carbonate rock, near the fault, the discharge rate and pressure per fracture was therefore initially less than away from the fault where the density of fractures is less. In other words, more outlets were initially available to drain discharge water near the fault than away from the fault and lower discharge pressure near the fault. Thus, the higher discharge pressures and rates in fractures away from the fault resulted in preferential solution weathering.

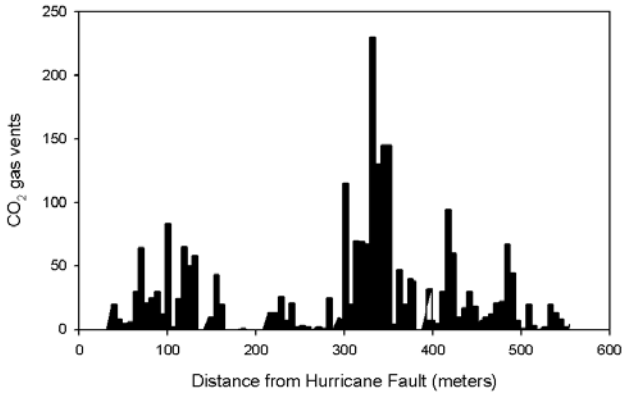

Figure 3 CO_2 gas inflows with increasing distance from the Hurricane Fault

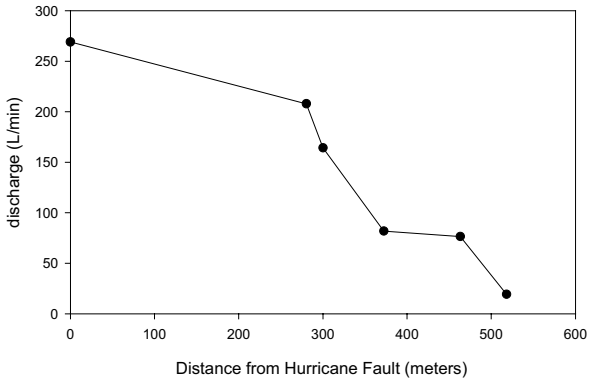

Figure 4. Measured groundwater inflows with increasing distance from the Hurricane Fault

REFERENCES

Bieke RF (1998) Interim geologic map of the Hurricane quadrangle, Washington County, Utah. US Geol Surv Open File Report 361, 142 p.

Stewart ME, Taylor WJ, Pearthree PA, Solomon BJ, Hurlow HA (1997) Neotectonics along the Hurricane Fault in Utah & Arizona, Part 1. Brigham Young University Geology Studies, 42, pt 11, p. 235-254

Deep-seated aquicludes in a fractured carbonate environment, West Bank

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A b s t r a c t : Drilling of deep water wells in the West Bank, Palestine in an environment of strongly karstic and fractured carbonates has proven a challenge to the geological and hydrogeological interpretation of logging, coring, sampling and pump testing. Due to the available local technology, pump tests are performed in single hole open bottom wells, 500 to more than 800 m deep and with water levels between 200 and 600 m below ground level. Test results and long term operation from various boreholes indicate the wide range of conditions with respect to degree of fracturing and karstification, rock lithology and aquifer parameters.

INTRODUCTION

It is generally understood that the Mountain Aquifer in the West Bank is divided into an Upper aquifer of Cenomanian-Turonian age and a Lower aquifer of Upper Albian age. The two aquifers are seen to be separated by an aquiclude of impervious Lower Cenomanian **Yatta** formation or *Beit Meir & Moza* formations in **Palestinian** and *Israeli* terminology, respectively. The Lower aquifer is underlain by thick series of Neocomian to Lower Albian pelitic sediments, referred to as **Kobar** group aquiclude in **Palestinian** terms. Specific literature on Yatta and Kobar is scarce. Despite geological evidence, most hydrogeological studies (see References) simplify both. Yatta and Kobar are described as homogenous overall aquicludes or sometimes also as leaky aquicludes: Yatta as "the middle aquiclude", Kobar as "the bottom aquiclude" (tab.1). However, drilling and test results suggest a more complicated picture: The special nature of the so called "middle aquiclude" and the "bottom aquiclude" has to be refined in the light of the new drilling results. Both undergo laterally considerable facies changes and reach locally aquifer conditions suitable for well abstraction.

YATTA – "MIDDLE AQUICLUDE"

In a typical section, Yatta has a top yellow marl layer (*Moza*) and a bottom blue clay section (*Beit Meir c*). Its middle (*Beit Meir a and b*) is rather aquiferous. However, due to lateral facies changes, either one or both of the impervious horizons can thin out or change into carbonate lithology. Accordingly, Yatta can be part of the Upper aquifer (like in Ein Samia) or part of the Lower aquifer. It can form an independent middle aquifer (mostly perched) or be rather an overall aquitard. However, its impervious horizons at the top and bottom can undergo lateral facies change to carbonate lithology, thus creating one uninterrupted aquifer, as found in **Audala** well, near Nablus. Here, the Upper and Lower Aquifer were encountered as one unit, not sufficiently separated by Yatta. Yatta was found to be more of a carbonatic than of a marly nature. The gamma-ray log shows peaks between 20 and 40 API units only (fig.1). Water levels, logging and pump testing data confirm this result

Ein Samia well # 6 was first pump tested in the Upper aquifer alone, then in the Upper and the top of the Lower aquifer together and finally in both aquifers together. The main section of Yatta was found to be very productive (Transmissivity ~1000m^2/day) and part of the phreatic Upper aquifer. In the pump test analysis, a new "Deflection point" method was used to determine and confirm the position of the bottom of the Upper aquifer (bottom *Beit Meir b*).

KOBAR – "BOTTOM AQUICLUDE"

The Kobar aquiclude is composed of 300-400m thick series of marl, clay and shale, forming a powerful bottom aquiclude of the Mountain Aquifer. Exploration wells targeted this formation (Beit Dajan well) as well as the deep Ramali sandstone, Ramali being known as Kurnub aquifer in neighbouring areas and countries (Ein Senia well #7).

Ein Senia well tapped Neocomian – Aptian strata that were found to be without recharge. Rock cuttings, cores and geophysical logs were analysed to reveal the nature of the formations. Only Ein Qinya, Nabi Sa'id and Hatira formations were found to have a lithology that allows for some aquifer potential, however with insufficient recharge.

Age		Formation	Literature	EinSamia # 6 [m]		Audalah [m]		EinSenia # 7 [m]		Beit Dajan [m]	
Cenomanian	Up.	'Amminadav	**Upper Aquifer**	Upper Aquifer	122	dry aquifer	103	not drilled		not drilled	
	Lower	Moza	**Aquiclude (YATTA)**		21	----	27				
		Beit Meir a			59	water level	80				
		Beit Meir b		Aquiclude	35	at bottom	22				33.5+
Albian	Upper	Kesalon	**Lower Aquifer**	"middle" Aquifer	22	Aquifer	33			dry	18
		Soreq		Aquitard	79		76				80
		Giv.Ye'arim		Lower Aquifer	68		60	dry	43+		58.5
		Kefira			147		120	weak: no recharge	185		74
	Lower	Qatana	**Bottom Aquiclude (KOBAR)**	Bottom Aquiclude	48+	Bottom Aquiclude	5+	Aquiclude	52	weak: 5m fract	82.5
		Ein Qinya		-		-		weak Aquifer	72	good: 18m fract	57
Aptian		Tammun d						Aquiclude	89	weak: 14m fract	46.5
		Tammun c							86	Aquiclude	71.5
		Tammun b							43		61
		Tammun a							37		48
Neocomian		Ein Al-Assad						Aquitard	38		47+
		Nabi Sa'id						weak Aquifer	67	-	
		Hatira	**Deep Aquifer**						113+		

Table 1. Comparison of formation thickness and aquifer properties between literature and 4 new boreholes

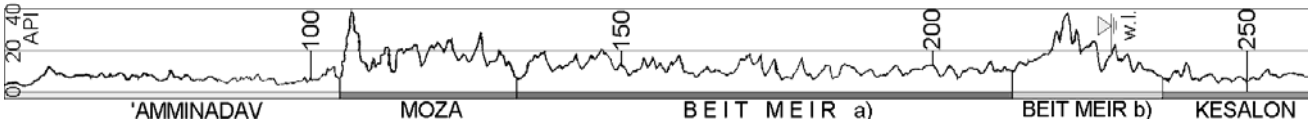

Figure1. Natural γ-ray log in Audala well (peaks in API-Units, depth in m below ground level)

Beit Dajan well was drilled to the Lower Albian. The upper third of Kobar was found to be a composite series of aquitards and aquicludes of marl and shale, interbedded with nodular limestone horizons. These limey horizons of Qatana, Ein Qinya and Upper Tammun attain an overall thickness of 200m. They contain three highly fractured sections of an accumulative thickness of 41m, which provide preferential inflow to the well (fig.2). Thus Upper Kobar here can be considered a multi-layered aquifer, albeit with restricted recharge: The well is suitable for supply on a local scale only. Hydrocarbon-age analysis and several pump test analysis methods confirm the findings of coring, sampling and logging in this double porosity fractured aquifer.

Kobar, usually a strong aquiclude, can be aquiferous in some areas, for parts of its section. While the Ein Qinya formation was already known as a local aquifer, the new findings show that Qatana and even Upper Tammun can also be locally aquiferous.

The yield however, is restricted due to the lack of direct rainfall recharge in these usually deeply buried series. In other areas, Kobar undergoes a lateral facies change, and Qatana and especially Tammun are purely aquicludal (as in Ein Senia well).

Future well drilling has to take these findings into account. Well design and the testing program must pay attention to the specific nature of the "aquicludes" in respective well locations. Failure to address these issues can lead to surprises in the findings, technical problems during construction and problems in the long-term operation.

REFERENCES

Aliewi AS *et al.* (1995) Design, construction, and chemical analysis of Deir Sharaf well No 2a and assessment of the properties of the Upper Beit Kahil aquifer in the Nablus area. Dept of Civ Eng, Univ of Newcastle/Tyne, 74 pp

Camp, Dresser, McKee, Inc. / Morganti (1998) Task 18 - Study of the sustainable yield of the Eastern aquifer basin, Fina;l report. USAID Contract No. 294-C-00-96-90560-00, 80 pp

Guttman J, Zukerman C (1995) A model of the flow in the Eastern basin of the mountains of Judea and Samaria from Fari'a Stream to the Judean Desert. TAHAL 01/95/66, Tel Aviv, 72 pp

Kroitoru L, Mazor E, Issar A (1992) Flow regimes in karstic systems: The Judean anticlinorium, central Israel. In: Ed. by Back W *et al.* (eds) Hydrogeology of selected karst regions. H. Heise Verlag, Hannover 339-354

Shachnai E (1980) Yarqon Tanninim – Beer Sheva basin, updating of the hydrogeological model. TAHAL 01/80/12, Tel Aviv 59 pp

Weinberger G *et al.* (1994) The Yarkon-Taninim groundwater basin, Israel: Hydrogeology, case study and critical review. J Hydrol 161:227-225.

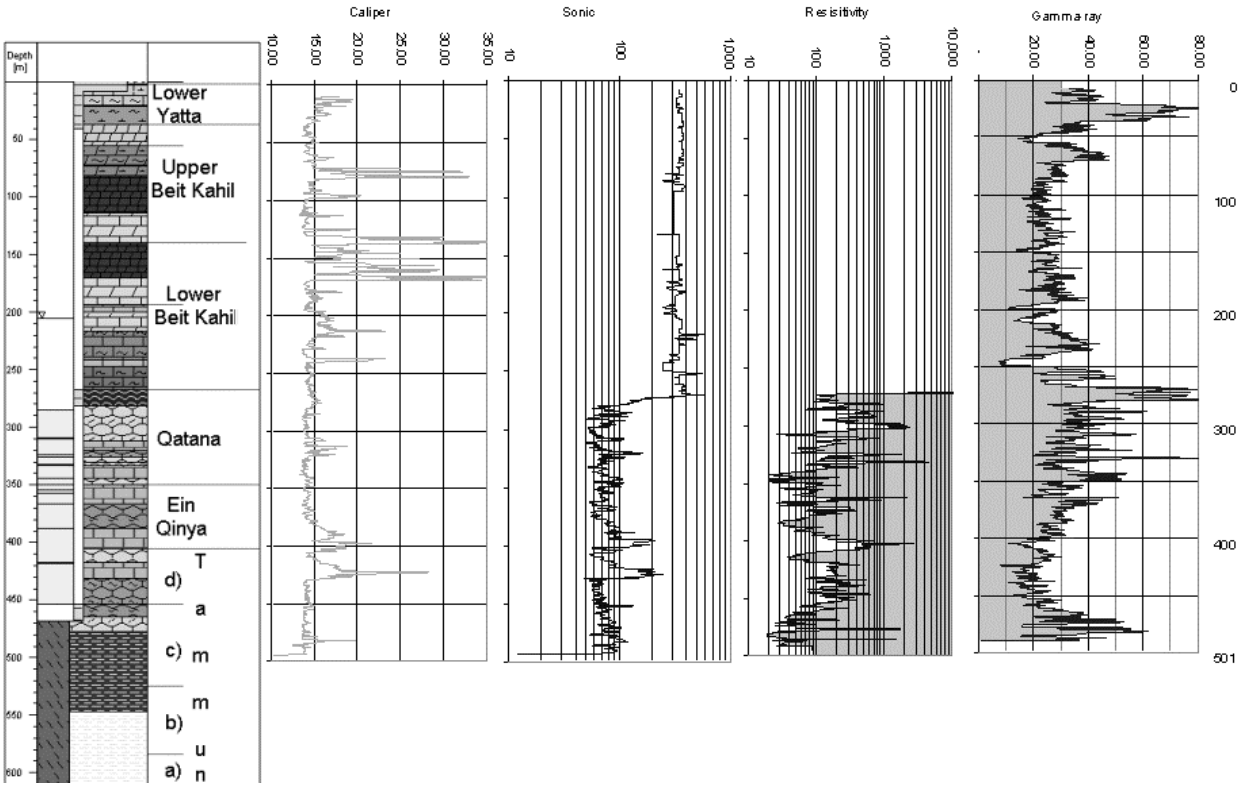

Figure 2. Geophysical log of Beit Dajan well with 3 fractured horizons at ~310, 390 & 415m bgl

Hydrogeological study of the western lowlands and adjacent highlands of Ethiopia

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The study concentrated on the preparation of methodology for hydrogeological mapping and groundwater potential assessment additional to the transfer of know-how and manpower training. The work was carried out as a joint Czech-Ethiopian project where the Czech Government financed participation of the Czech experts within the program of Technical Aid Assistance and the Ethiopian Government financed participation of the Ethiopian hydrogeologists on the project.

Guidelines for compilation of hydrogeological and hydrochemical maps of the Ethiopian territory in 1: 250 000 scale, including a standardised legend and contents of explanatory notes have been prepared. The standardised legend was compiled based on the latest published recommendation to the international legend of the Hydrogeological Map, and experience from the Czech Republic and Ethiopia. The methodology was applied on the Asosa - Kurmuk area (NC36-7 and NC36-8 sheets). The area is 18,850 km^2 in extent and is bounded by the Ethiopian-Sudanese border on the west and longitude 36 E on the East, and latitudes 10 and 11 N on the South and North. The highest peak of the area reaches 2601 m; the lowest place on the map 500 m a.s.l. is where Abbay River (Blue Nile) crosses the Ethiopian border.

A thick sequence of layered Tertiary basalts and interbedded sediments represents the main aquifer within the study area additional to fractured aquifers hosted in Precambrian crystalline basement and marble, and Mesozoic sandstone overlaid by scattered porous aquifer developed in Quaternary deposits. Particular attention has been paid to the basaltic aquifer of the Asosa plateau in the upper Hoha river catchment where hydrogeological characteristics and groundwater potential were studied in detail.

The hydrogeological and hydrochemical data gathered during desk and field study were included into a database for further interpretation (wells logs, Piper graphs). GIS was used for compilation of the first version of hydrogeological and hydrochemical maps of the study area. Aquifers were classified based on the type of permeability and coloured in green for fissured and karstic aquifers hosted in basalt and marble, in blue for alluvial sediments and brown-red for low productive fissured aquifer hosted in basement rocks.

The groundwater is of basic Ca–HCO_3 and of transitional Ca-Mg-HCO_3 type. The frequency of basic and transient types is equivalent at the Asosa plateau aquifer. TDS in groundwater varies from 20 mg/L to 800 mg/L. The groundwater is suitable for drinking water supply.

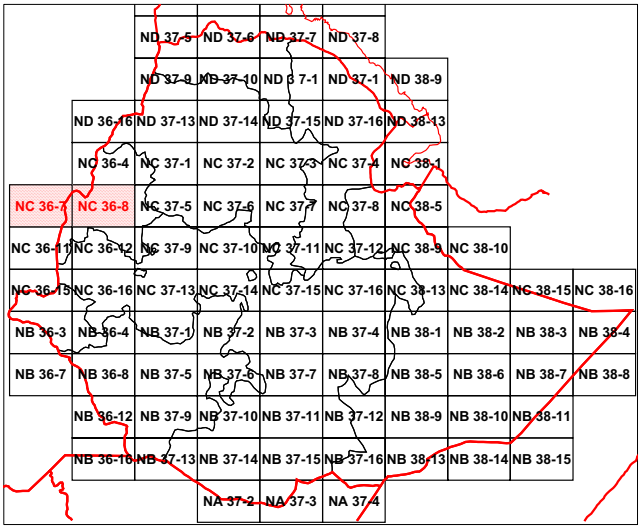

Figure 1. Location of the map sheets 1:250 000

The role of a fractured aquifer between two karstic systems: connection zone or groundwater barrier?

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A b s t r a c t : The Cork Harbour area of SW Ireland is characterised by a series of E-W trending Variscan anticlines and synclines, the former cored by Upper Devonian Old Red Sandstone (ORS), and the latter by karstified Lower Carboniferous limestones. Overburden of variable thickness, mostly glacial till, overlies bedrock, but sand and gravel deposits also occur. Major groundwater aquifers exist in both the bedrock and the overburden. The area is cut by a series of vertical, N-S trending Variscan compartmental faults, so the ORS coring the anticlinal ridges, can be regarded as a fractured rock aquifer on a local scale. On a regional scale, it represents a barrier between the two karstic systems, but the N-S faults provide interconnections between the two limestone aquifers. The storativity of the ORS sequence is relatively limited, but in the study area gives characteristic well yields ranging from 200-500 m^3/day. The chemical composition of groundwater from the fractured aquifer is mainly of the HCO_3-Ca type, with mineralisation ranging up to 300 mg/L.

INTRODUCTION

Situated at the mouth of the R. Lee in SW Ireland, Cork, with a population of 250,000 in its environs is the second largest city in Ireland. The Lee drains into Cork Harbour, a glacially eroded, almost completely enclosed basin, connected to the Atlantic Ocean by a narrow entrance. The area investigated is a 1,000 km^2 region encompassing Cork City and Harbour (Fig.1).

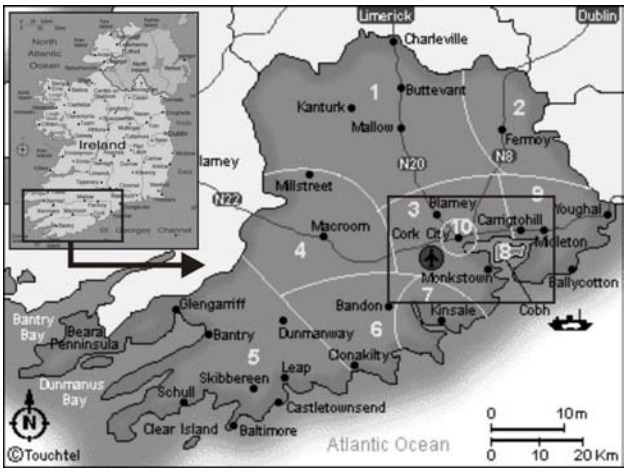

Figure 1. Location and geographical setting of the study area

Rapid industrial growth in the Cork area has led to a significant risk of groundwater pollution, particularly within shallow fractured and intergranular aquifers, formed in the Devonian sandstones and in fluvioglacial gravels respectively. A research project, initiated in 2000, to assess groundwater resources and quality within the Cork Harbour area, and jointly funded by the two local authorities administrating the area, Cork County Council and Cork City Council (Allen and Milenic 2001), is evaluating these risks, and will be completed shortly.

GEOLOGY OF THE AREA

The Cork Harbour area of SW Ireland lies within the late Carboniferous Variscan Orogenic Belt of SW Ireland. The area is characterised by a series of E-W trending anticlines and synclines, the former cored by U. Devonian Old Red Sandstone (ORS), consisting of a sandstone/shale sequence, and the latter by massive karstified L. Carboniferous limestones (Fig.2.). Two major limestone-cored synclines in the Cork Harbour area, the Cork-Midleton Syncline and the Cloyne Syncline, are separated by the intervening ORS-cored Great Island Anticline. Other ORS-cored anticlines, the Rathpeacon Anticline and the Church Bay Anticline occur to the north and south of the Cork-Midleton and Cloyne Synclines respectively. Overburden of variable thickness, mostly glacial till, overlies bedrock, but sand and gravel deposits, particularly infilling deep buried valleys, also occur.

Variscan deformation and recrystallisation has obliterated primary porosities in both the ORS and the limestones, but gave rise to secondary porosity due to intense fracturing, which in the limestones controlled later karstification. The whole sequence is cut by numerous, vertical, N-S trending, late Variscan compartmental faults, which cut through both the ORS-cored anticlinal ridges and the limestone cored synclines, so the relatively impermeable ORS can be regarded as a fractured rock aquifer on a local scale. On a regional scale it represents a barrier between the two karstic systems, but the N-S faults provide interconnections between the two limestone aquifers.

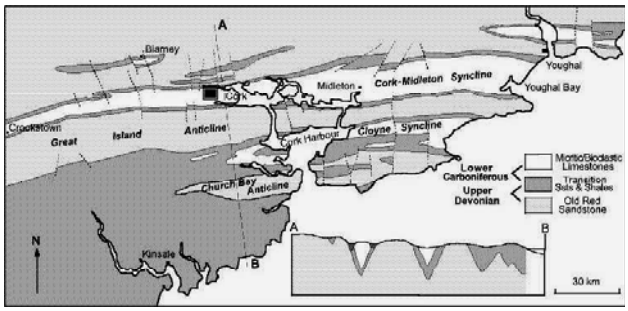

Figure 2. Simplified geology of the study area (after Allen *et al.* 1999)

BASIC HYDROGEOLOGY

Major groundwater aquifers occur in both bedrock and the overburden. The Cork-Midleton and Cloyne Synclines are cored by intensely karstified limestones, which have significant storage capacity and transmissivity properties. Overlying these bedrock aquifers, are important ribbon aquifers represented by gravel-infilled buried valleys. These aquifers are a major resource.

THE FRACTURED AQUIFER

Aquifer Delineation

A fracture analysis of the ORS within the Great Island Anticline indicates that the dominant fracture set is parallel to the compartmental faults and approximately perpendicular to the orogenic trend with a mean strike of 345°-165° i.e. N-S. Less important thrust-related fractures parallel to the regional strike have a mean orientation of 075°-255° i.e. E-W. These two sets of fractures provide the main storage for groundwater in the ORS.

Other groundwater reserves are located in the relatively thick weathered zone of this fractured aquifer.

Taking the Great Island Anticline alone, the aquifer is 60km in length, 2-5km in width, with a 10-15m thick weathering zone. The fractured nature of the aquifer suggests probable deep circulation through the fracture network.

Groundwater Recharge

The dominant process of recharge in the fractured aquifers is through direct recharge by precipitation. In the Cork area, annual precipitation is of the order of 1200mm/year, but evapotranspiration amounts to approximately 500mm/yr, so the effective precipitation is 700mm/yr.

Surface run-off varies with topography. In the Cork area the ORS-cored anticlines form relatively steep-sided ridges, with incised valleys. Although precise measurements of the proportion of run-off are as yet lacking, it is estimated that 75% of the available rainfall runs off at the surface.

For the Great Island Anticline fractured aquifer, the effective infiltration (i_{ef}) can be estimated as 170 mm/yr.

Although 170mm/yr may infiltrate into the ground, the fractured aquifer is overlain by variable thickness of relatively impermeable clay-rich glacial till. Thus percolation through the glacial till will be slow and a significant proportion of the infiltrated precipitation will be held on the clays in the till as soil moisture, so the proportion of infiltrated rainwater, which ultimately recharges the water table, may be quite small.

There is also possible recharge from the adjacent karst aquifer, but since the ORS underlies the ridges and the karstified limestones the broad E-W valleys, it is unlikely that the fractured aquifer receives any recharge from the karst aquifer, and in fact more probable that the fractured aquifer feeds the karst aquifer.

Hydrogeological Parameters

Based on the fracture analysis in the Great Island Anticline, linear and areal coefficients of fracture density for the ORS have been determined. Surface values of up to 1% are indicated. Taking into account the effects on surface fractures of physical and chemical weathering processes, and the closure of fractures with depth due to confining pressure, an overall effective porosity for the fractured aquifer of around 0.1% is estimated. However, more intensely fractured and deeply weathered zones are associated with the compartmental faults, which are usually exploited by streams, so effective porosity in these zones is probably considerably enhanced.

Groundwater Discharge Sources

Discharge from the Great Island Anticline fractured aquifer occurs by a variety of processes :

1. Minor springs - representing the sources of a number of stream rising in the Great Island Anticline, with discharges of the order of 0.1-1.0 L/s.
2. Private water wells - over 300 registered wells, ranging in depth to up to 50 m, with discharges of 0.1-5.0 L/s.
3. Baseflow - most of the streams draining from the Great Island Anticline into the Cork-Midleton and Cloyne Synclines are fed under normal low flow conditions by groundwater - up to 50% of the streamflow is probably derived from groundwater sources.
4. Recharge of the karst aquifers – discharge into the adjacent karst aquifers of the Cork-Midleton and Cloyne Synclines is probably significant, particularly via the compartmental faults.

Evaluation of Groundwater Resources

Using the classical water balance formula, to delineate groundwater reserves, values of around 2,000,000 m^3 of groundwater, are indicated.

Hydrochemistry

Hydrochemical data, representing a compilation of over 50 analysed samples from the Great Island Anticline are presented in Tab.1. The groundwater composition is of the HCO_3-Ca type, with mineralisation ranging up to 300 mg/L. On the basis of oxygen and deuterium isotopic analyses, a meteoric origin is indicated for the groundwater of the fractured aquifers.

Table 1. Chemical composition of groundwater from the fractured aquifer

Parameter	Unit	MAC	Range of Values
Temperature	^oC	-	12.0-14.0
PH	-	6-9	6.2-7.9
Na	mg/L	150	8.50-24.77
K	mg/L	12	1.23-8.33
Ca	mg/L	200	25.57-48.72
Mg	mg/L	50	3.86-13.51
HCO_3	mg/L	-	62.83-250.10
SO_4	mg/L	250	6.17-27.74
Cl	mg/L	250	17.25-34.59
NO_3	mg/L	50	3.38-32.27
Hardness	$CaCO_3$	-	82-224
EC	µS/cm	1500	246-492
Total Diss.Solids	mg/L	1000	162-325

Groundwater vulnerability and protection

As mentioned earlier, rapid industrial growth in the Cork area has led to greater risk of groundwater pollution. The Geological Survey of Ireland in co-operation with the Irish EPA and the Dept. of the Environment has developed a groundwater protection scheme methodology (GSI 2003).

Although overlain by glacial drift, overall in the upland areas underlain by the fractured aquifers, overburden is relatively thin and the shallow aquifer is vulnerable to pollution, particularly from a large number of private septic tanks, many of which are inappropriately sited too close to bedrock. Agricultural production and land fertilisation are other potential sources of groundwater contamination as the fractured aquifers are largely given over to farming. In addition a landfill has operated in the southern part of the Great Island Anticline for the past 20 years, although it is now in the process of closure. The landfill is sited in a valley exploiting a compartmental fault, and occupies a quarry used to extract fill for a deepwater port facility in Cork Harbour, so highly fractured bedrock is exposed, and the potential for pollution of groundwater is high.

Connection Zone or Barrier?

Due to their poor primary permeability, the fractured ORS aquifers of the Cork Harbour area behave on a regional scale as barriers to groundwater movement between the karst aquifers they separate. Despite this, the N-S compartmental faults cutting the E-W Variscan folds of the Cork Harbour area provide probable connection pathways between the karstic aquifers. However, a groundwater watershed exists between the Cork-Midleton and Cloyne Syncline karst aquifers, occurring within the Great Island Anticline. Thus, shallow local groundwater flow between the two synclines will be inhibited. Nevertheless, although no actual proof exists, deep regional circulation between the karst aquifers probably occurs via the compartmental faults.

REFERENCES

Allen AR, Milenic D (2001) Preliminary Assessment of Groundwater Resources and Groundwater Quality in the Cork City/Harbour Area, Ireland, In: Proceedings of the XXXI IAH Congress, Munich, Germany 2:1119-1125

Allen AR, McGovern C, O'Brien M, Leahy L, Connor BP (1999) Low enthalpy geothermal energy for space heating/cooling from shallow groundwater in glaciofluvial gravels, Cork, Ireland. In: Proceedings of the XXIX IAH Congress, Bratislava, Slovak Republic 655-664

GSI (2003) Aquifer protection scheme, County Cork (Southern Division): Interim. GSI Report (Draft), Dublin

Fracture networks: a case study from the Chalk aquifer in East Anglia

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A b s t r a c t : In the present study a method has been developed to upscale flow characteristics across fractured networks, with an intended application to the risk of transport of particulates in the Chalk aquifer. A numerical model was built to consider flow through individual fractures based on field work at Hunstanton cliff in East Anglia. Fracture survey was carried out to give a quantitative description of fracture distribution and characteristics. Fractures in the network were modelled as finite segments, and orientations and positions were randomly distributed using the FRACMAN code to match the statistical properties measured in the field. This work involves generating a large number of conditional realizations to establish possible flow pathways across the domain.

INTRODUCTION

Fractures are considered to be the primary pathways allowing flow and contaminant transport within the Chalk aquifer. Haw and Farmer (1993) suggested that the hydraulic behaviour of a rock mass is determined by the geometry of the fracture system. Other geometric properties of individual fractures are also important, because aperture and connectivity are the most critical properties in controlling transport. They determine travel times and the lengths of flow paths in the Chalk, and hence affect the degree of contaminant attenuation through processes such as dispersion, diffusion and microbiological degradation (Foster 1993).

For fractured media, heterogeneity typically occurs over a broad range of scales. To date, no single numerical model can fully address all aspects of the complex hydrological processes involved at different scales. Sposito (1998) suggested that discrete models by simulating flow through individual fractures will solve in some way the level of heterogeneity of the media, but results will depend on knowledge of field site, scale of interest and purpose on investigation. Field characterisation of fractures encourages the development of a modelling framework where fractures were considered as local heterogeneities. Numerical simulations of flow and transport in fractured rocks have been studied by many researchers lately using the discrete approach for which spatial structures of a fracture network and flow and transport in individual fractures need to be described in detail. However, it is difficult to move from conceptual models to numerical simulations of actual aquifers, as the latter require accurate field information on the geometry and transmissivity of individual fractures in order to analyse the hydraulic behaviour of the chalk rock.

Recently, numerical models have been focusing on stochastic analysis of data by considering fracture geometric parameters and transmissivity as random variables whose probability functions are estimated from field data. By generating random parameters, a fracture network is created and flow through the network can then be solved by computer simulation. This paper develops a conceptual model based on field measurements. A key issue was to postulate a model that describes the variability of the data and can be used to extrapolate from the data to the unknown by finding patterns of regularity within the fractured media. An upscaling technique was used for parameter values and conceptual models to be assigned to the larger scale.

Flow and geometric parameters of the media were defined on a local scale (~10 to ~100 m) based on field data and to extend those measurements and their statistics to a greater scale, it was necessary, first to quantify and relate those parameters and their associated statistics on the scale of measurement, and then to determine them on another scale.

To guide upscaling we examined the relationship between hydraulic conductivity and measurement scale in pumping tests in the Chalk. This small-scale fracture network models were designed to give a statistical match to fracture patterns and fracture-bounded block sizes measured in the field, and Chalk transmissivity at local scales. Upscaled models must match field transmissivity values at larger scales. Block size distribution was then used as a second conditioning test, realisation that failed to produce the field distribution of block sizes being rejected. The model was designed to give a representation of local scale flows and contaminant pathways. They were modelled by means of randomly generated fracture networks that are built from simple inclined planes using FRACMAN code. Multiple realisations ($\sim 10^3$) by this approach provided a range of local scale models to use in upscaling.

METHODOLOGY

In constructing local scale models, it was necessary to establish the degree of heterogeneity in the fracture geometry. This was determined from statistical analysis of the detailed fracture patterns measured at a specific location (the cliffs at Hunstanton). The method consisted of collecting data of fracture geometry (such as fracture orientation, spacing, length and aperture). Further information from fallen fracture-bounded blocks found near the cliff was also included in the analysis, as their size distribution helped to improve the property assignment within the model. The resulting 3D fracture network consisted of seven different fracture sets that had similar orientation and probability of occurrence, but different lengths.

Individual fractures were recorded directly on the site using a photomosaic technique, and then represented by a plane of finite extent. Fracture characteristics were mapped and grouped in families according to direction. To define the different fracture sets we used the stereographic projection method (Philips 1971). Then, the statistical mean and standard deviation were computed for every fracture set, providing the basis for stochastic representation of the same set in models with the same characteristics as observed in the field. These were generated for a similar sized domain as the Hunstanton cliff section, using the FRACMAN code.

FRACMAN MODEL

FRACMAN (Golder, Inc.), was used in this study to give a local scale (~50m) representation of fracture networks. This code considers spatial variability in geometric and hydrological parameters inferred from statistical analysis. Scale effects were avoided by constructing local models at the same scale as the field section.

By generating random parameters, a fracture network can be constructed and the flow through it solved by computer simulation. Repeating the network generation and flow simulation many times makes it possible to assess the variability in flow and transport through different networks at the local scale. Each realisation is consistent with the spatial statistics of the sample location.

FRACMAN's Poisson Rectangle Model was used to represent the fracture distribution. The boundary of the box generation region was set up as 50m x 5m x 5m and fractures were randomly generated in the region interior (Fig.1). The idea behind this method was to find values for densities and length distributions of rectangular fractures with Poisson spacings that give the observed field distribution of trace lengths on a plane with the orientation and length of the Hunstanton cliff.

RESULTS AND DISCUSSION

A illustrative example is given below of a 5mx5mx5m box which is relatively limited in extent, but contains a realisation of the steeply inclined fracture sets seen on the cliff face at Hunstanton. A summary of some of the statistical data measured for these these fractures in the field. is shown on Tab.1.

Set	Strike Mean	SD	Plunge Mean	SD	L(m) Mean	SD	N
A	107.5	8.5	40.2	17.4	3.4	1.2	15
B	93.7	11.3	42.5	18.4	3.4	1.3	10
C	24.28	9.3	31.2	9.6	3.2	1.4	18
D	20.3	9.4	41.8	1.5	3.5	1.7	10
E	141	12.4	35.5	11.2	3.5	1.5	6
F	56.5	7.7	38.7	9.4	3.1	1.4	4

Table 1. Statistical analysis of fracture sets. (n=63)

Trace planes were generated by FRACMAN in directions perpendicular and parallel to the cliff face to perform analysis of data and to detect patterns of regularity. The statistics displayed for fracture intersections on these traceplanes (as shown in Fig.1) can be directed compared with the field data. The fracture density and length distribution within the FRACMAN models were varied until the best match was obtained between the statistical properties of traceplanes (fracture lengths, spacings, and number of intersections between sets) and the field properties of the cliff section. The best fracture densities and length distributions were then used to generate multiple random realisations of statistically similar networks on a 50m x 5m x 5m region. More spatially extensive numerical simulations show that percolation of the network is determined by fracture length distribution. Scale effects in bulk flow and transport properties may arise from errors in fracture length distribution.

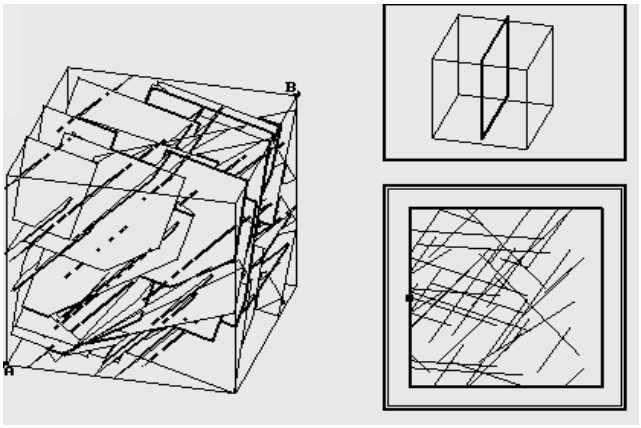

Figure 1. FRACMAN realisation region and display of trace plane

Representative fracture aperture values were not available from field measurements (though aperture variability was determined for a few exceptionally wide example fractures, cf. Bloomfield 1997). Aperture and aperture distributions were estimated by trial and error conditioning of each realisation, determining whether its bulk hydraulic conductivity felt within the known distribution of values from pumping tests in East Anglian Chalk. The distribution of bulk K across all FRACMAN realisations was compared with the known distribution to provide as close as match as possible.

Transport properties can now be defined for each realisation. Each model can be characterised by a 6 x 6 binary matrix indicating whether fracture pathways exist between its six faces. For particle transport, a further condition can be introduced of whether pathways have continuously large enough apertures to allow a particle of given size to pass across the region.

With this technique we improve representation of fluid flow and transport in fracture networks at local scales. The final problem is to upscale from a FRACMAN block to a 500m x 500m x 50m MODFLOW cell (Fig.2). This can be achieved by tiling the larger volume with randomly selected blocks. Further upscaling from 500m x 500m to a 10km by 10 km flow model can also be achieved by a second generation of tiling. This should lead to enhanced model conceptualisation where it will be possible to draw a map of probability of transport between any cell and the target cell. Such a model should in turn produce a more accurate basis for groundwater risk assessment.

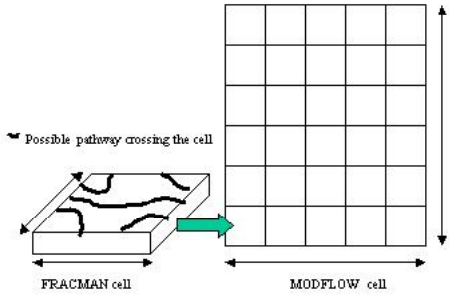

Figure 2. Upscaling technique from a FRACMAN box to a MODFLOW cell

REFERENCES

Bloomfield J (1996) Characterisation of hydrologically significant fracture distribution in the Chalk: an example from Upper Chalk of Southern England. Journal of Hydrology 184:355-379

Derwitz W, Lee G, Geier J (1998) FRACMAN interactive Discrete Feature Data Analysis, Geometric Modelling, and Exploration Simulation, User Documentation, Version 2.6, Golder Associates Inc, 248 pp

Foster SSD (1993) The Chalk aquifer-its vulnerability to pollution. The Hydrologeology of the Chalk of North West Europe. Clarendom Press, Oxford, 93-112 pp

Haw L, Farmer I (1993) Fluid Flow in Discontinuous Rocks. Chapman & Hall. London, 38-82 pp

Kitanidis PK (1997) Introduction to Geostatistics: Applications in Hydrogeology, Cambridge University Press, United Kingdom, 246 pp

Phillips FC (1971) The Use of Stereographic Projection in Structural Geology, Edward Arnold, London

Sposito G.(1998) Scale Dependence and Scale invariance in Hydrogeology, Cambridge University Press, United Kingdom, 420 pp

Fracture pattern influence on groundwater discharge along the tectonic border of karst aquifers (Velino Valley, Central Italy)

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A b s t r a c t : This paper reports the results of hydrogeological, hydrochemical and fracture pattern studies conducted along the northern tectonic border of the S. Vittorino Plain, an intramontane basin located in Central Italy. The two karst aquifers encircling the Plain are fed by many springs with a total discharge of 30 m^3/s. The northern border of the Plain, consisting of extensional faults of Pleistocene age, holds springs with different hydrochemical characteristics. The study of the local fracture pattern showed the influence of the direction and type of fractures (width, fills, etc.) on groundwater circulation. Indeed, the NS- and NE-SW-trending fractures facilitate groundwater flow (S and SW flowpaths). Conversely, in zones of dominant EW- and NW-SE-trending fractures, the flow from the northern karst aquifer is prevented, while groundwater from the southern aquifer can cross and flow beyond the Plain and the hydrochemistry of local springs is clearly affected by deep gas leakage.

INTRODUCTION

The permeability boundaries of karst aquifers in recent and active tectonic areas often coincide with their tectonic borders (Petitta and Tallini 2001). This situation is common in the Central Apennines, where the main aquifers are represented by karst ridges (whose alluvial and terrigenous deposits correspond to aquitards and aquicludes, respectively). The tectonic borders of these aquifers, featured by extensional faults of regional scale, accommodate springs with high mean discharge (often exceeding 1 m^3/s) (Boni *et al.* 1986). These active extensional faults also hold fluids that are closely related to the volcanic or hydrothermal activity that the Tyrrhenian margin of the Apennines experienced in the Quaternary (Faccenna *et al.* 1993). This geodynamic setting favours the migration of deep-seated gases and fluids (e.g. CO_2 and H_2S) towards the surface along the extensional faults, inducing substantial changes in groundwater hydrochemistry (Ciotoli *et al.* 1998).

The study area, i.e. the northern border of the S. Vittorino intramontane plain, in the Velino River Valley (Central Italy), has two regional-scale karst aquifers, which feed high-discharge (total discharge: 30 m^3/s) springs and interfere with deep gas leakage along the faults.

HYDROGEOLOGICAL SETTING

The S. Vittorino Plain (Fig.1), located in northern Latium, 80 km NE of Rome, in the Velino River Valley, is a morphological depression that may be defined as an intramontane basin (Cavinato and De Celles 1999). The basin lies between the two main Meso-Cenozoic depositional environments of the Central Apennines: the Latium-Abruzzi carbonate platform and the Umbria-Marche pelagic sequence. A set of NNE-SSW-trending faults puts the two environments in contact with each other. These faults, occurring on the north-western slope of the Plain, derive from a compressive tectonic stage of the Apennine orogenesis (Bigi *et al.* 1990). In Pleistocene times, dominantly extensional tectonic processes downthrew the local carbonates towards NW-SE, NE-SW and N-S. The Plain was filled by alluvial, fluvio-lacustrine travertine and scree deposits, with increasing thickness towards the centre of the Plain, reaching more than 200 meters. Over and above high seismicity (testified also by recent average-magnitude earthquakes), the area exhibits evidence of active tectonic processes (Faccenna *et al.* 1993).

From a hydrogeological point of view, the S. Vittorino Plain is home to major regional aquifers, which are recharged by the carbonate platform outcropping on the SE slope of the Plain (Boni *et al.* 1986, Boni *et al.* 1995). High-discharge piedmont springs lie both along the Velino River Valley (streambed springs) and on the northern side of the Plain, namely along the tectonic border of the northern karst aquifer, although the water table matches the topographic surface along the entire border.

Permeability variations in the alluvial deposits induce seepage from the south-eastern regional karst aquifer towards the streambed springs, located on the northern side. An additional factor triggering groundwater flow towards N-NW is represented by the mostly gaseous fluids which upwell along recent and/or active tectonic lines. In the Plain a large number of sinkholes testifies the interaction between groundwater, extensional faults and deep fluids upwelling (Capelli *et al.* 2000, Salvati and Sasowsky 2002). These fluids are mainly composed of carbon dioxide, which acts as a carrier of H_2S, CH_4, NH_4, He and Rn gases (Ciotoli *et al.* 2000).

The end result is a large number of springs with very different hydrochemical characteristics, depending on origin from the SE karst aquifer or from the northern one, water circulation in the Plain deposits and mixing with upwelling deep fluids.

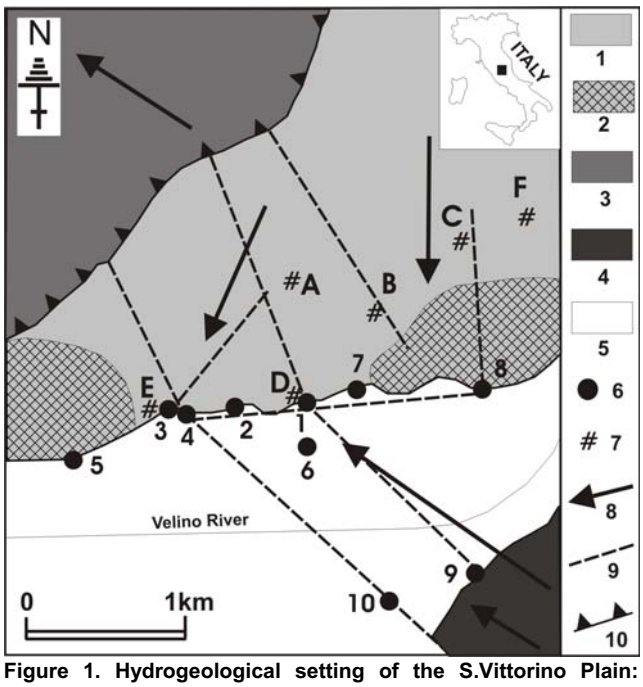

Figure 1. Hydrogeological setting of the S.Vittorino Plain: 1: northern aquifer; 2: travertine; 3: overthrust hydrogeological unit; 4: southern aquifer; 5: Plain aquifer; 6: spring monitored; 7: fracture pattern site; 8: groundwater flowpath; 9: main fracture and fault; 10: overthrust.

HYDROGEOLOGICAL AND STRUCTURAL SURVEYS

A detailed study of groundwater location and hydrochemistry, as well as of the fracture network along the aquifer border was conducted from 2000 to 2001 (fig.1).

The Plain hosts more than 80 springs. Their discharge and main parameters (electrical conductivity, temperature, pH) were measured in different seasons. Discharge was monitored in the Velino River and its tributaries in order to assess the contribution of streambed springs (Boni *et al.* 1995, Capelli *et al.* 2000).

Based on the findings from hydrogeological analyses, 10 hydrochemical analyses were carried out on as many springs (fig.2). The springs were selected in such a way as to represent the widest possible range of conditions, in terms of both typology (contact with the carbonate aquifer, gases, fractures, etc.) and variability of their physico-chemical parameters.

Finally, the geological-structural features of the northern border of the Plain were investigated in detail thanks to six geomechanical stations (tab.1).

code	A	B	C	D	E	F
main directions	NW-SE E-W	N-S E-W	N-S NE-SW	NW-SE	N-S NE-SW	E-W N-S
silt and clay	NW-SE	E-W	absent	NW-SE	N-S	E-W
width (cm)	<5	5-20	>20	<5	5-20	<5

Table 1. Fracture patterns along the northern border of the Plain. The site code refers to fig.1.

The comparison of the collected data showed a direct connection between the location of the main fractures and the one of low-salt springs. Other springs lie along the tectonic border of the northern karst aquifer, at times near unconformities: in these instances, water salinity and chemistry proved to be significantly different and clearly affected by deep gas upwelling. Finally, other lower-discharge springs, located along the tectonic border, appeared to be unrelated to fracture lines.

A comparative examination of fracture directions near the springs showed that: i) in zones where fractures are dominantly NS- and NE-SW-trending, waters have lower salinity and their chemistry is typical of karst aquifers; conversely, ii) in zones where fractures are EW- and NW-SE-trending, waters have a much higher salt content and their chemistry is surely affected by deep gas upwelling. Also the type of fills and the width of fractures demonstrated to have an impact on the features of the spring waters: silty-clayey fills and smaller width (<5 cm class) are more frequent along E-W and NW-SE fractures, which thus correspond to high-salinity springs. By contrast, along N-S and NE-SW fractures, silty-clayey fills are usually absent and their width is larger (5-20 cm and >20 cm classes).

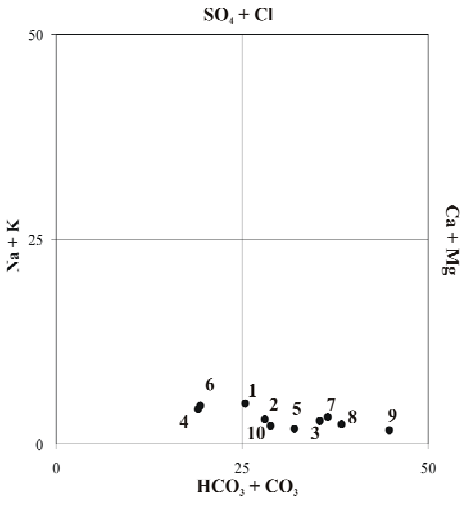

Figure 2. Chebotarev diagram of the groundwater of the Plain. The sample code refers to fig.1.

CONCLUSIONS

The findings from hydrogeological, hydrogeochemical and fracture network surveys along the northern aquifer border of the S. Vittorino Plain show the dominance of karst groundwater in zones where fractures and faults are NS- and NE-SW-oriented, thus easing the flow from the northern karst aquifer to the border springs. In fact, groundwater flowpaths in the karst aquifer have the same directions as those of fractures and faults. In zones where E-W and NW-SE fractures prevail, groundwater flow from the northern karst aquifer is prevented and the spring hydrochemistry is clearly influenced by deep gas leakage.

These findings suggest the following remarks:

- in the karst aquifer discharge zones, spring location is influenced by the fracture pattern and, in some cases, spring discharge is related to the type of fractures;
- in zones where the aquifer border is in contact with active tectonic faults, spring hydrochemistry might be affected by deep-seated gas and fluid migration toward the surface;
- fracture and fault orientation, facilitating gas leakage or groundwater flow from the karst aquifers, gives rise to a non-random distribution of springs along the aquifer border;
- the chemistry of waters, strongly affected by deep fluid upwelling along the unconformities bordering the Plain, enables to distinguish their origin fairly easily.

In conclusion, in a complex hydrogeological setting like the investigated one, spring distribution along the border of the aquifer is highly influenced by the location of the main unconformity lines, as it commonly occurs in karst aquifers, but also by their orientation. In tectonically active zones, such influence may be more easily identified thanks to the presence of groundwater with abnormal chemistry, clearly affected by deep gas upwelling.

It is therefore easy to identify the origin and recharge zones of the individual springs, with groundwater resource conservation and management implications.

REFERENCES

Bigi G, Cosentino D, Parotto M., Sartori R, Scandone P (1990) Structural model of Italy, sheet 4, scale 1/500.000, CNR Italy

Boni C, Bono P, Capelli G (1986) Schema Idrogeologico dell'Italia Centrale. Mem. Soc Geol It 36:991-1012

Boni C, Capelli G, Petitta M (1995) Carta idrogeologica della alta e media valle del fiume Velino, Com. Mont. Velino VI° zona

Capelli G, Petitta M, Salvati R (2000) Relationship between catastrophic subsidence hazards and groundwater in the Velino Valley (Central Italy). In: Carbognin L (ed.) Proceedings 6th Intern Symposium on Land Subsidence, Ravenna 123-135

Cavinato GP, De Celles PG (1999) Extensional basins in the tectonically bimodal central Apennines fold-thrust belt, Italy: Response to corner flow above a subducting slab in retrograde motion. Geology 27(10):955-958

Ciotoli G, Di Filippo M, Nisio S, Romagnoli C (2000) La piana di S.Vittorino: studi geologici, geomorfologici, geofisici e geochimici. Mem. Soc Geol It 56:297-308

Ciotoli G, Guerra M, Lombardi S, Vittori E (1998) Soil gas survey for tracing seismogenic faults: a case study in the Fucino basin, Central Italy. J Geoph Res 103:23781-23794

Faccenna C, Florindo F, Funiciello R, Lombardi S (1993) Tectonic setting and sinkhole features: case histories from western Central Italy. Quaternary Proceedings 3:47-56

Petitta M, Tallini M (2001) Groundwater vulnerability assessment at the tectonic boundary of a karst aquifer (L'Aquila-Scoppito Plain - Central Italy). In: Mudry J, Zwahlen F (eds) 7th Conference on limestone hydrology and fissured media, Sci Tech Envir, Mem HS 13:285-288

Salvati R, Sasowsky I (2002) Development of collapse sinkholes in areas of groundwater discharge. J Hydr 264:1-11

The origin and extent of some fissures in sandstones

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A b s t r a c t : In some sandstone aquifers, it appears that fissures are important for carrying flow into wells but are not important in regional flow. Some fissures appear to be of limited extent around the wells. It is suggested that these are artificial pseudo-karstic features, formed by the action of drilling and/or pumping the wells.

INTRODUCTION

In some sandstone aquifers, laboratory (intergranular) measurements of hydraulic conductivity are usually much lower than values obtained from measurements on individual boreholes using packer systems. There is also clear evidence from borehole TV and geophysical logs that fissure-flow is important in the flow of groundwater into boreholes. This implies that fissures contribute significantly to the *local* transmissivity of the formation.

On the other hand, *regional* values of hydraulic conductivity obtained from modelling are often closer to intergranular values, suggesting that fissures are not significant on the regional scale. In combination, these observations suggest that fissures are present but not interconnected to form regionally transmissive systems. Previous work (Price 1994) has indicated that some fissures are of limited extent around the boreholes; this helps to explain why fissures with large apertures have relatively low measured transmissivities (Price 1994).

This leads to the question: how can isolated fissures form in sandstone? I suggest that some at least of the fissures are artificial pseudo-karstic features, formed when the boreholes are constructed or pumped; they originate as layers or lenses of poorly-cemented sandstone, which will be referred to as 'incipient fissures'. Sand from these incipient fissures moves into the borehole during or after drilling, as a result of the seepage force created by water movement into the borehole, creating the void. To test this theory, I have used simple numerical models to give an insight into the manner of development of these fissures and to indicate the magnitude of their effect on well yield and drawdown.

CONCPTUAL MODEL

The conceptual model used as the basis for the calculations is shown in Fig.1. Radial distances are measured from the centreline of the well (r = 0). Other symbols are:

r_w = well radius, r_f = extent of developed fissure, R = outer boundary of modelled domain. The domain boundary is a constant-head boundary. The upper and lower boundaries are no-flow boundaries.

The fissure is assumed to develop as a circular disc centred on the well.

NUMERICAL MODEL

The numerical model used here is a mesh-centred finite difference model, created on a spreadsheet using Angoss Smartware™. The model is pseudo-radial flow, in that the width of each cell (the direction at right angles to r) is made equal to πr. The vertical and radial mesh spacings were scaled to account for anisotropy.

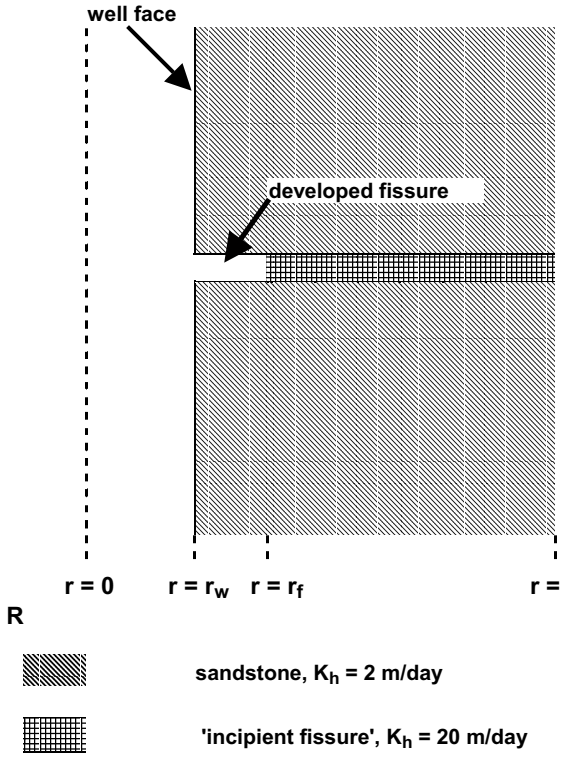

Figure 1. Conceptual model of development of fissure from an 'incipient fissure' (layer of poorly-cemented sandstone)

RESULTS

Most British wells in sandstone have diameters of less than 1 m. Models have therefore been run with values of r_w of 0 (infinitesimal diameter) and 0.5 m to cover the complete range. The model described here has r_w = 0, R = 40 m, and considers a layer of 2 m in thickness with a horizontal weakly-cemented layer (the incipient fissure) 0.05 m in thickness at 1 m depth. The sandstone has horizontal hydraulic conductivity (K_h) as indicated in Fig.1. The head at the domain boundary (r = 40 m) is 10 m. Pumping lowers the head in the well to 0 m. When this happens, the head distribution in the sandstone will be as shown by the broken line in Fig.2.

The steep hydraulic gradient immediately around the well means that there will be a large seepage force acting on the sand grains immediately behind the well face. In the cemented sandstone, the strength of the cement will usually be sufficient to resist this force, but in the incipient fissure the weakly-cemented grains will be carried into the well. This will result in a fissure developing around the well (Fig.1). In the model, it is assumed that the transmissivity of the fissure is 100 m^2/day.

This is a relatively modest value for a sandstone fissure (see, for example, Price *et al*. 1982); for an opening of 0.05 m, it corresponds to a K_h value of 2000 m/day, the value used in the model for the developed portion of the fissure.

If the weakly-cemented material in the incipient fissure is uniform, and the flow field is uniform to the well, the fissure will develop as a disc. As the fissure begins to develop, the head distribution will change, with the head along the incipient fissure/developed fissure taking on the distribution illustrated by the solid line in Fig.2, where the fissure has developed to a radius of 1.5 m. Now the steepest hydraulic gradient occurs at the periphery of the developed portion of the fissure, and the seepage force will be pushing grains into the fissure and then into the well. This will cause the fissure to continue to develop further away from the well, as long as the hydraulic gradient at the fissure periphery is great enough to create sufficient seepage force. As the head loss along the fissure is relatively insignificant, this seepage force is likely to persist while the head difference is maintained between the outer boundary of the sandstone and the well.

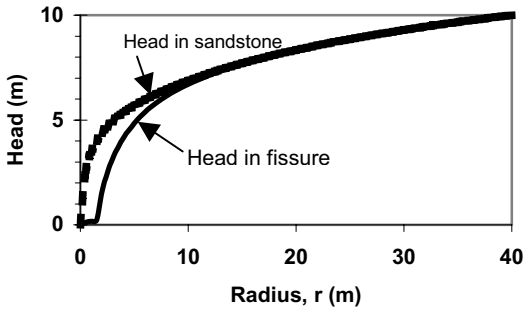

Figure 2. Head distribution in the sandstone around a well and in a developing fissure

In practice, wells are not developed at constant drawdown but at a series of constant production rates. As the fissure develops, the well will become more efficient, developing what the oil industry refers to as a *negative skin effect*, and the specific capacity will increase. If the well is being pumped at a constant rate, the drawdown in the well will reduce, the hydraulic gradient will lessen and the seepage force will eventually become insufficient to develop the fissure further. The decrease in drawdown that will occur in a well of infinitesimal diameter being pumped at a rate of 10 litres/s is shown in Fig.3.

If the pumping rate is increased, then the hydraulic gradient will increase again and the fissure will develop further. The removal of sand from the developing fissure is seen as sand production as the well is first pumped. As fissure development ceases, sand production also ceases but will recur the first time that the well is pumped at a higher rate.

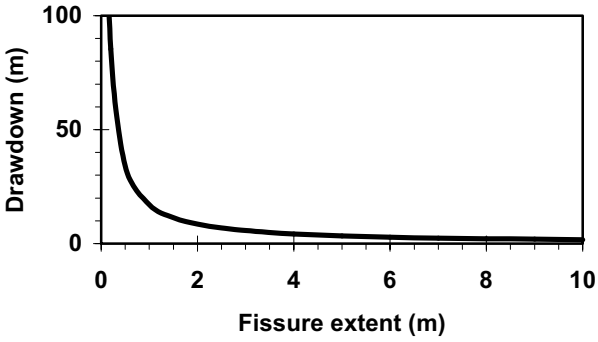

Figure 3. Decrease in drawdown as fissure develops around a well being pumped at constant rate

In reality, there will be several, perhaps many, fissures developing as the well is first pumped, and their eventual developed extent will depend on a combination of factors including the extent of weakly-cemented layers or lenses. The action of drilling the well, especially if an air-flush system is used, may also be sufficient to create a gradient and initiate fissure development.

SUMMARY

Some fissures in sandstones may be important in collecting water from the aquifer and carrying it into wells, without being involved in regional flow. These fissures are of limited extent around wells. The presence of these apparently isolated voids can be explained by the fact that they are artificial features, created by the drilling and pumping of the well. They will develop around the well. When they collect sufficient water to reduce the drawdown, the gradients and seepage forces that led to their development will be reduced so that their growth is effectively self-limiting. Thus the presence of fissures around production and monitoring wells does not necessarily imply that fissures are taking part in regional flow or pollutant movement. This needs to be borne in mind when defining protection zones.

REFERENCES

Price M (1994) A method for assessing the extent of fissuring in double-porosity aquifers, using data from packer tests. Future groundwater resources at risk: International Association of Hydrological Sciences, Publication No. 222: 271-278

Price M, Morris BL, Robertson AS (1982) A study of intergranular and fissure permeability in Chalk and Permian aquifers, using double-packer injection testing. Journal of Hydrology 54:401-423

Developing a conceptual hydrogeological model for a fractured bedrock formation

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A b s t r a c t : This paper presents the methodological framework for developing a Conceptual Hydrogeological Model (CHM) in a fractured bedrock formation. A case study exemplifies the synthesis of primary data that includes the geology, geophysics, hydrology, and hydraulics of the site. The CHM includes: identification and interaction of hydrogeological units, recharge mechanisms, hydrogeological parameter estimation, and delineation of hydraulically-interconnected fracture paths.

A Conceptual Hydrogeological Model (CHM) was developed for a metamorphic fractured bedrock formation contaminated with chlorinated solvents. The site is located in Portsmouth, NH, USA. The CHM was developed by integrating information on the geology, geophysics, hydrology, and hydraulics of the site.

Geologic data included information on stratigraphic setting, mineralogy, structural geology, and drilling cores analysis (including microscopic studies of thin-sections.) Five boreholes were drilled down to fractured-bedrock strata, and completely cored; eight real-time drilling parameters (including input/output drilling-water flow and drill rate) were recorded at three of these boreholes. Conventional borehole-geophysics, acoustic televiewer, optical televiewer, and omni-directional radar logs were obtained for all Drilled Wells (DW). Geophysical logs were the basic tool to define the DW depth intervals to isolate for Hydraulic Testing (HT).

Hydrologic inputs included statistical correlation between atmospheric pressure changes, rainfall, and temperature meteorological records and up to two-years records of water levels data obtained with pressure transducers installed in DW and five pre-existing weathered-bedrock Monitoring Wells (MW) (Fig.1).

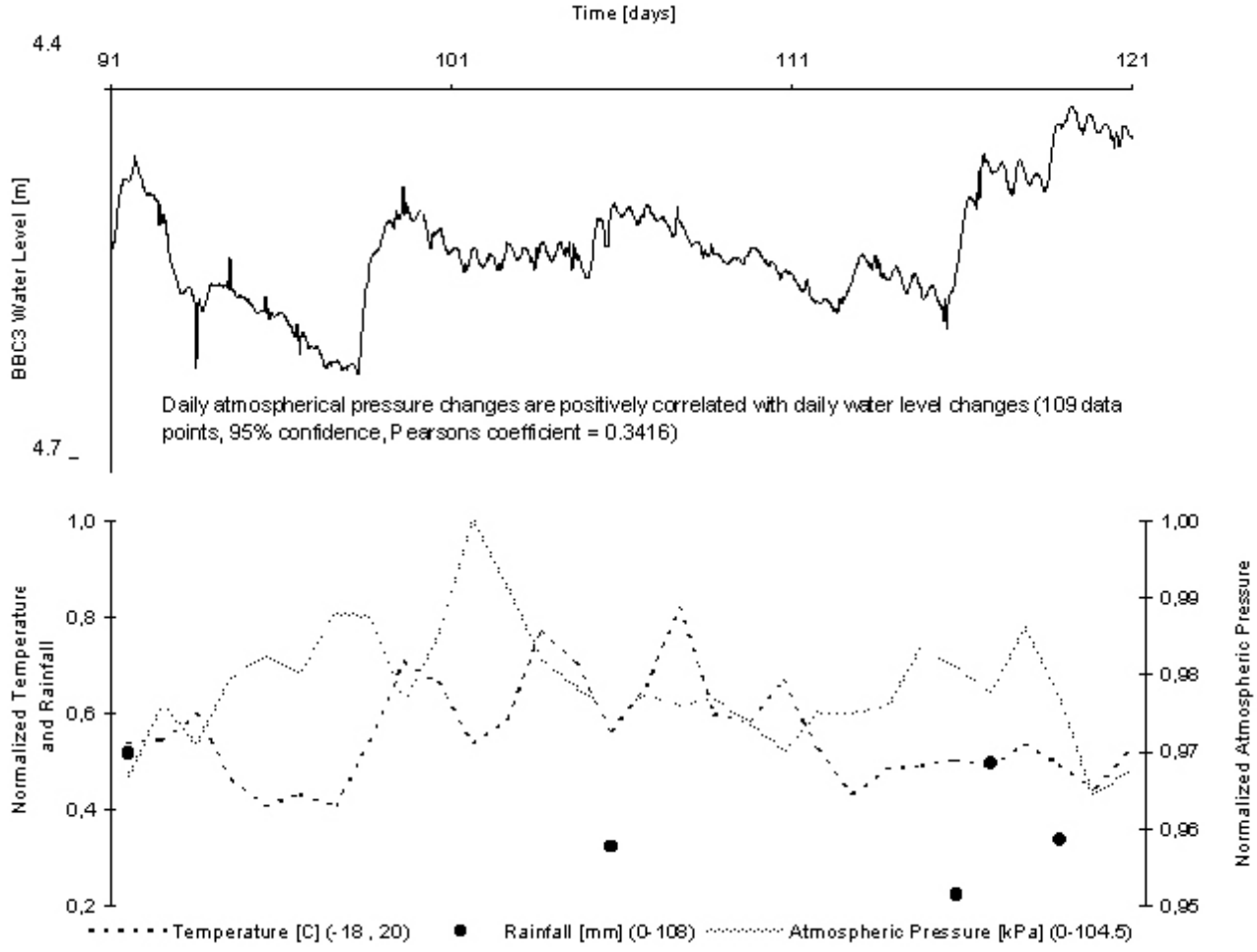

Figure 1. Well BBC3 (fractured bedrock) water level, and site meteorological parameters variations during April, 2002

An intensive hydraulic characterization of the site included: a 15-day site-scale Pumping Test (PT), more than twenty straddle-packer PT with MW, more than two hundred Slug Tests (ST) at isolated depth intervals at each DW, and more than one hundred Large Displacement Slug Tests (LDST) (Pulido-Silva *et al.* 2003). HT results were interpreted with the analytical-homogeneous models widely accepted in literature (Marsily, 1986), and with numerical-heterogeneous models coded in the HyTests software (Pulido-Silva *et al.* 2003) (Fig.2). In addition, to assess hydraulically-connected fractures, DW and MW water-level responses were analyzed during drilling and HT of each DW (Fig.3).

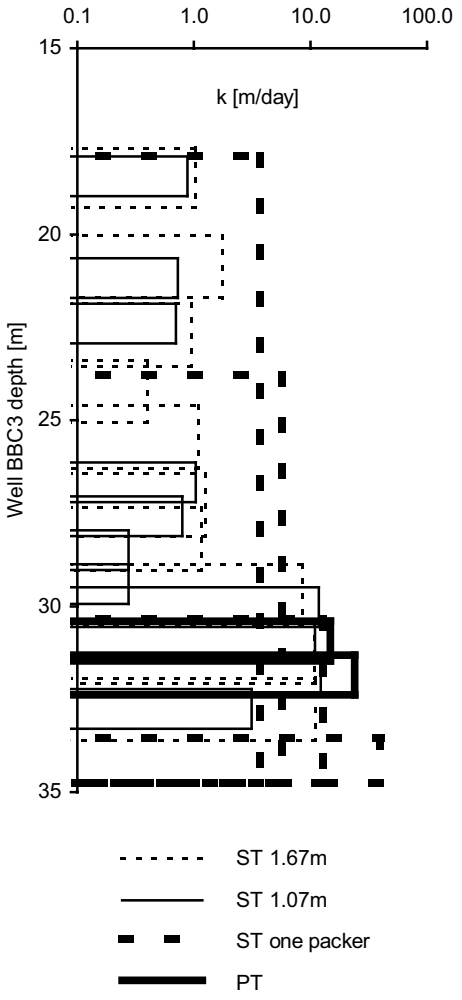

Figure 2. Hydraulic conductivity profile for well BBC3 (ST analyzed by Cooper method; PT analyzed by HyTests homogeneous model)

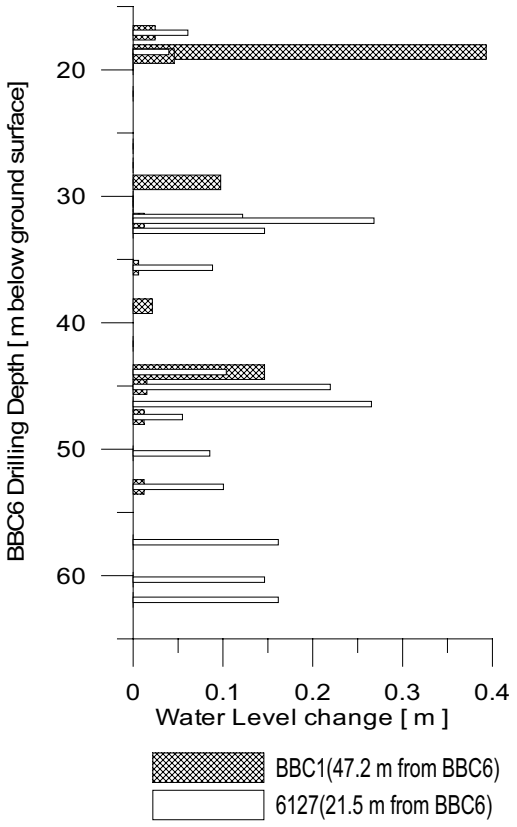

Figure 3. Water level changes at wells BBC1 (fractured bedrock) and 6127 (weathered bedrock) during well BBC6 drilling (fractured bedrock). (Bar width differences are just for visualization improvement)

The CHM includes: identification and interaction of hydrogeological units, recharge mechanisms, hydrogeological parameters estimation, and delineation of hydraulically-interconnected fracture paths. Currently, the CHM is being used to develop a mathematical hydrogeological model for the site, and to understand transport mechanisms and flow paths for a proposed bioremediation strategy.

REFERENCES

Marsily G (1986) Quantitative hydrogeology, 1st English-edition. Academic Press, Orlando 440 pp

Pulido–Silva G, Ballestero TP, Kinner NE (2003a) Large displacement slug tests. In: IAH International Conference on Groundwater In Fractured Rocks–Proc

Pulido–Silva G, Ballestero TP, Kinner NE (2003b) HyTests: a set of numerical models for hydrogeologic parameters estimation. In: IAH International Conference on Groundwater In Fractured Rocks–Proc

Analysis of fractures for groundwater resources identification and their management: an integrated approach using RS and GIS

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Groundwater in a hard-rock (igneous and metamorphic) terrain is multivariate because of its relation to topography, depth, and extent of weathered material overlying unweathered bedrock; and because of the size, nature, density, orientation, and interconnection of joints and faults. Hence, multidisciplinary surveys are necessary to understand the part played by these features in groundwater occurrence. As a result, exploration for groundwater in a hard-rock terrain has proved to be complex. Modern technologies such as remote sensing for studying geological, structural, and geomorphological conditions, along with conventional surveys, can be highly helpful in determining the nature of fractures (open or closed) and their pattern over large areas. In the hard rock terrain, Fractures and dykes play a major role in groundwater occurrence and movement. A particular Fracture pattern development indicates a particular deformation period and on its stress regime. Intrusive bodies of dolerite dykes are the zones of older fracture zones. So understand the different stress regimes and ruptural deformation period the integrated analysis of fractures and dykes is conducted and identified the direction of open tensile fractures that are more favourable zones for groundwater occurrence in upper Ponnai river basin, which presents in drought-prone Rayalaseema region of Andhra Pradesh, India. The study area lies between North latitudes: 13°18'30" - 13°37'50" N and East longitudes: 78°51'45" - 79°17'10".

Indian Remote sensing satellite IRS 1D LISS III data of FCC (Path & Row: 101 - 64, dated 6APR 2001) is visually interpreted for geological, structural, geomorphological and hydrogeomorphological studies and field checks are conducted. Geologically the study area is underlined by Archaean granitic gneisses, intrusive bodies (i.e., dolerite dykes, pegmatite veins and quartz veins) and recent age of alluvium deposits. Geomorphologically, the study area has been classified as: Denudational hill (DH), Residual hill (RH), Dome massive (Dm), Inselberg (I), Pediment Inselberg Complex (PIC), Pediment (P), Shallow weathered Pedeplain (PPS), Moderately Weathered Pediplain (PPM), Deeply weathered Pediplain (PPD), Valley fills (VF), Structural Valley (SV) and Alluvial Plain (AP). The predominant trends of the fractures are ENE-WSW and NW-SE; minor trends are NE-SW, N-S, and E-W. Major trend of dykes is in ENE-WSW, EW, NW-SE and NS directions. Groundwater potential zones are identified by integrating the geological, structural, geomorphological, hydrogeological, and hydrological and slope data. Suitable sites for rainwater harvesting structures are recommended for the development and management of the water resources for the future generations.

Hydrogeological study of Saldoran fractured karstic aquifer in Zagros thrusted zone, Iran

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A b s t r a c t : Saldoran fractured karstic aquifer is located in the Zagros thrusted zone (high Zagros) which is in the western part of Iran. In addition to remarkable precipitation, presence of fractures and fissures and cold dry climate of the area are providing appropriate conditions for karstification. Form of precipitation (snow), the lack of considerable runoff in surface catchment area, rapid response of system to recharge, turbidity of the spring water during the peak of discharge and physiochemical analysis results also show that structural factors which conduct the rain and snow-melt water into the aquifer, can provide a suitable underground flow path in this shallow karstic system.

STUDY AREA

Saldoran fractured karstic aquifer is located in the western part of Iran (50° 15′-50° 45′ E and 30°-32° 30′ N), which is in the Zagros thrusted zone (high Zagros).

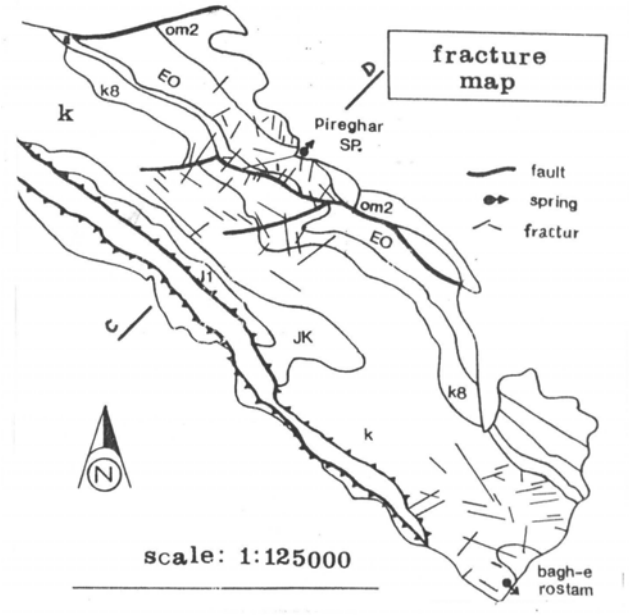

Figure 1. Geological map of study area

HYDROLOGIC CONDITIONS

In addition to remarkable precipitation, presence of fractures and fissures and cold dry climate of the area are providing appropriate conditions for karstification. The greater part of annual precipitation is in the form of snow, which falls in winter and melts with increasing environment temperature in early spring (March).

GEOLOGICAL SETTING

Geologic formations of this anticline in decreasing order of age are the Sarvak limestone (Albian-Turonian), Pabde-Gurpi marls and shales (Santonian-Oligocene), Kashkan red conglomerate (Eocene) and Asmari-Jahrom dolomite (Paleocene-Pliestocen).

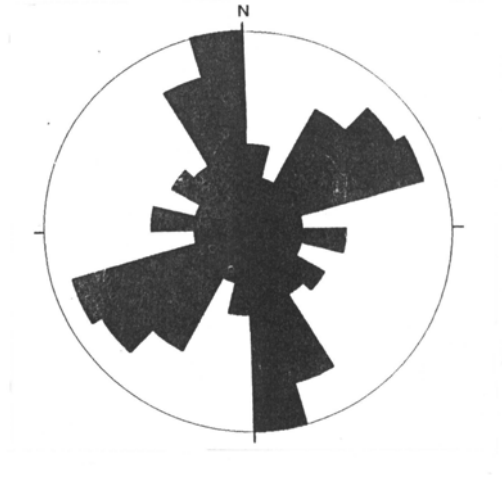

Figure 2. Rose-diagram of fractures in study area

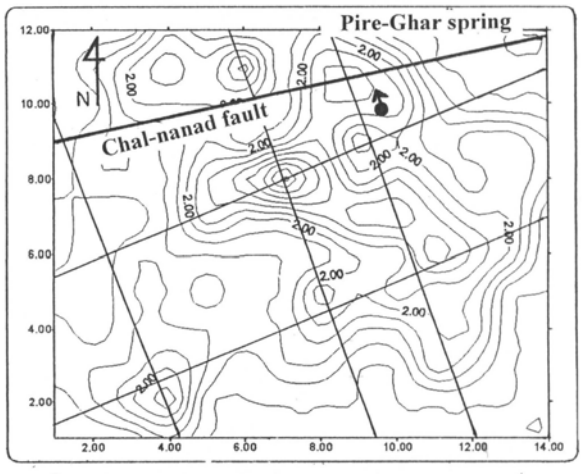

Figure 3. Iso-fracture map of Pire-Ghar catchment area

STRUCTURAL FEATURES

There are two sets of joints and fractures in this anticline, which are produced by several faults due to vicinity of the main Zagros thrust. Depending on the degree of fracturing that appears in the rock along the faults, we can distinguish broken and fissured zones. These zones are very permeable and water flows around, along and through these zones. The limestone and dolomite strata are highly permeable and deeply karstified, dipping about 40°-60°.

METHOD OF STUDY

The main discharge point in the northern flank of Saldoran anticline is Pire-Ghar spring (with main discharge 1.5 m^3/s). In order to study the characteristics of this aquifer, the major ions, EC, temperature and discharge of the spring water were measured every two weeks for ten months during 1998-1999.

DISCUSSION

The spring hydrograph shows four recession coefficients (α_1, α_2, α_3 and α_4) and two different flow regimes, which is dominated by conduit flow. Study of the structural features in addition to physiochemical characteristics of spring water proves the type of flow regime to be of the kind of conduit flow too.

Form of precipitation, the lack of considerable runoff, rapid response of system to recharge, turbidity of the spring water during the peak of discharge and physiochemical analysis results also show that structural factors which conduct the rain and snow-melt water into the aquifer, can provide a suitable underground flow path in this shallow karstic system. Furthermore it seems that the Chal-Namad fault (across the anticline axis) controls the emerging of the Pire-Ghar spring. In this system, the water is directed to the spring by the tectonic structures and by impermeable marls of Pabde-Gurpi formation.

REFERENCES

Azizzadeh M (1999) The role of basic fractures of Zagros in karstic aquifers balance: An analysis of Ghatar- Kazeroon fracture system, First Iranian geological and invironmental conference, Tehran, Iran

Fazeli A, Dehghan R, Baradaran A (1997) Karst study and its problems in relation to Third Kouhrang Tunnel, Second international karst symposium, Tehran, Iran

Raeissi E, Farhoudi G, Jahani H (1993) The effect of structural features on groundwater flow in folded karstic terrains, International symposium on water resources in karst with secial emphasis in arid and semi arid zones, Shiraz, Iran

Scanlon BP (1989) Physical controls on hydrochemical variability in the Inner Bluegrass karst region of centeral Kentuky. Ground water 27(5):639-646

Zamani A, Agha-amiri C (1993) The analysis of fractures and their relation to karstification in Gar abd Barmfirooz karstic region, International symposium on water resources in karst with special emphasis in arid and semi-arid zones, Shiraz, Iran

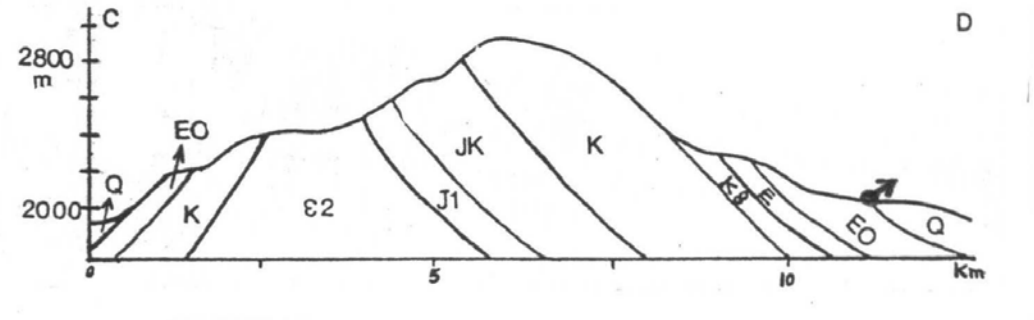

Figure 4. Cross-section of study area

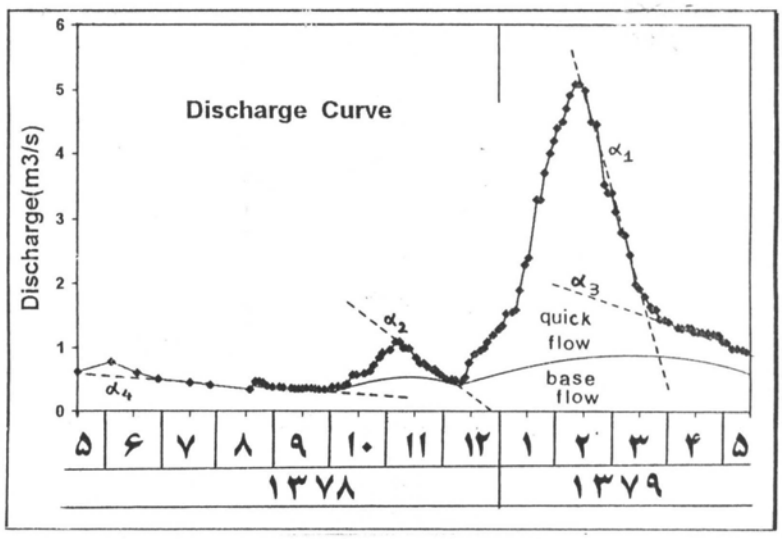

Figure 5. Hydrograph of pire-Ghar spring

Groundwater yield in hard rocks south of Oslo, Norway

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A b s t r a c t : A hydrogeological case study has been carried out in a hard rock area south of Oslo. The lithology comprises different Precambrian gneisses, amphibolitic rocks, and Permian granite. Fractures are measured in the field and on aerial photos. Almost 400 drilled wells are visited, and the wells relation to lithology and fracture directions has been examined. The study shows that the different Precambrian gneisses and the Permian granite have more or less identical yields in drilled wells. The amphibolitic rocks are clearly inferior. The main fracture directions are believed to have developed in a Precambrian stress field, and later reactivated during the formation of the Permian Oslo graben. Drilled wells connected to the Permian reactivated fracture directions have significantly higher yields than wells connected to other fracture directions. Furthermore, wells connected to the reactivated tensional and extensional directions have higher yields than those connected to the reactivated shear directions. Wells located in areas without visible fractures have low capacities.

INTRODUCTION

A hydrogeological case study has been carried out in a hard rock area south of Oslo. The lithology comprises different Precambrian gneisses (fine-grained leptitic gneiss, gneissified granitic rocks, granitic to quartz-dioritic biotite gneiss and biotite-muscovite paragneiss) along with Precambrian amphibolitic and gabbroic rocks and Permian biotite granite.

Fractures within the study area are measured both in the field and by stereoscopic interpretation of aerial photos. Almost 400 drilled wells with known depth and yield is visited in the field, and the wells relation to lithology and fracture directions have been examined.

YIELD IN RELATION TO ROCK TYPE

The study shows that the different Precambrian gneisses and the Permian biotite granite, on average, all have similar yields in drilled wells, c. 20 – 28 L/h per drilled m. The granitic to quartz-dioritic biotite gneiss is the superior. The gabbroic and amphibolitic rocks, however, are clearly inferior, yielding c. 9 L/h per drilled m.

The fine-grained leptitic gneiss seemed to be inferior to the other gneisses with an average yield of only 645 L/h in drilled wells as compared to the other gneisses average yields of c. 1200 L/h.

The wells drilled in the fine-grained leptitic gneiss, however are drilled only to supply single summerhouses, and are all very shallow. Average depth is only 32 m while average depth of wells within the other gneisses is 50 – 60 m. By dividing the yield (L/h) by the well depth in m, also the fine-grained gneiss get a yield of slightly more than 20 L/h per drilled m. Key figures for the investigated wells are given in tab.1.

Table 1. Key figures for the investigated wells
BG = Permian biotitic granite
AM = Amphibolitic and gabbroic rocks
LE = Fine-grained leptitic gneiss
GG = Gneissified granitic rocks
GQ = Granitic to quartz-dioritic biotite gneiss
BP = Biotite-muscovite paragneiss

	BG	AM	LE	GG	GQ	BP
Number of wells	87	16	9	96	122	45
Median yield (L/h)	745	230	380	580	750	560
Mean yield (L/h)	1280	445	645	1160	1515	1160
Mean depth	62	50	32	48	54	55
Mean yield per drilled m	20,7	8,9	20,2	24,2	28,1	21,1

YIELD IN RELATION TO FRACTURES

Most of the fractures in the investigated area are steeply dipping. Fig.1 shows fracture trends in the Precambrian rocks. The right hand side shows 1002 fractures surveyed in the field, while the left hand side shows 112 larger fractures taken from aerial photographs.

The Precambrian rocks have developed a complicated pattern of fracture directions connected to different periods of disturbances up through the earths history. The bedrock map of the area (Hageskov and Jorde 1980) shows that the earlier folded Precambrian rocks have been re-folded in a relatively late Precambrian folding phase along fold axes trending WNW.

The main fracture directions, N 0°, N 20° – N 40° and c. N 120° (fig.1) are supposed to have been created or reactivated during this folding phase. Based on the orientation of these fracture directions and the fold axes, it seems plausible that the maximum stress direction in this late folding phase was c. N 30°.

Theoretically, tensional fractures are developed parallel to the maximum stress direction, while shear fractures are developed at c. 30° angels to this direction. Extensional fractures (relief fractures) are developed parallel to the fold axes, at right angel to the maximum stress direction. By using this principle on the measured fracture directions, they are classified into shear fractures, tensional fractures and extensional fractures in fig.1.

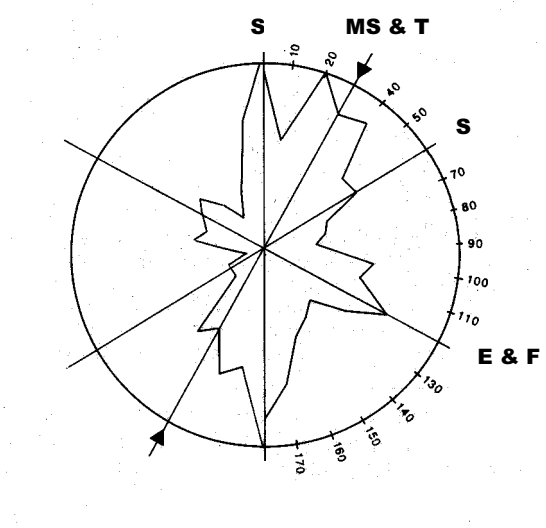

Figure 1. Fracture directions in the Precambrian rocks
S = Shear fractures
MS = Maximum stress direction
T = Tensional fractures
E = Extensional fractures (relief fractures)
F = Fold axes

The investigated area lies within or borders to the Permian Oslo rift. Thus the present fracture pattern is supposed to be mainly determined by Permian disturbances.

The Permian Oslo rift, which is running in a north-north easterly direction, was formed by tensional forces directed perpendicular to the rifts longitudinal direction. The Permian tensional forces were thus directed perpendicular to the maximum stress direction of the earlier described Precambrian stress field.

As tension has the opposite effect of compression, the same fracture system will develop by a tension along N 120° as by compression along N 30°. It is therefore to be expected that the Permian lateral spread of the crust led to a reactivation of the older Precambrian fracture system.

Tensional fractures are generally believed to be more permeable than shear fractures. Thus wells located by the tensional and extensional fractures trending N 30° and N 120° should generally have higher yields than wells located by the shear fracture directions N 0° and N 60°.

Less than 200 of the investigated wells with known yield and depth are drilled in fracture zones that are visible on the surface. To test the theory that tensional fractures generally are more permeable than shear fractures, all wells, independent of rock type, drilled in fracture zones are given in tab.2, with reference to the fracture directions.

Table 2. Well yields in relation to fracture directions

Fractue direction	Number of wells	Medium depth (m)	Medium yield (L/h)	Mean yield per drilled m
N 0°	36	47	2390	51
N 30°	46	41,5	2436	59
N 60°	6	55	1958	36
N 120°	17	50,5	2962	59
Others	67	52	1011	19

Tab.2 shows that the highest yields are obtained in the tensional and extensional directions N 30° and N 120°, with average yields of almost 60 L/h per drilled m. The shear fractures are inferior with c. 50 L/h per drilled m for the direction N 0° and c. 35 L/h per drilled m for N 60°.

The different yields obtained for the two shear directions are probably caused by a combination of weak development of the direction N 60°, and the fact that the direction N 0° is a pronounced Permian fracture direction (Ramberg and Larsen 1978).

Furthermore, the table shows that wells drilled at other fracture directions than the above mentioned, have pronounced inferior yields.

By comparing the mean yield per drilled m in tab.1 and 2, it also becomes evident that wells drilled in areas where no fractures are observed, have considerably lower yields than those drilled at fractures trending N 0°, N 30°, N 60° and N 120°.

Fractures in the Permian biotite granite are not easily explained in terms of a stress system. Most probably they are predominately formed during the consolidation process of the granite.

REFERENCES

Hageskov B, Jorde K (1980) Drøbak, bedrock map 1814 II. Preliminary edition. Geological Survey of Norway

Ramberg IB, Larsen BT (1978) Tectonomagmatic Evolution. In: Dons JA, Larsen BT (eds) The Oslo Paleorift. A Review and guide to excursions. Geological Survey of Norway

Hydrogeological characterisation of Palaeozoic hard rocks of Vicort and Algairén ranges (province of Zaragoza, Spain)

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A b s t r a c t : The study area is located in the Iberian Range (NE of Spain, Zaragoza province). From the hydrogeological point of view, the Palaeozoic hard rocks of the Algairén and Vicort ranges behave like an impervious body that separates two great aquifer units, the "Campo de Cariñena" Unit to the NE and the "Depresión de Calatayud" Unit to the SW. Although these Palaeozoic rocks can reach relatively high values of permeability in some areas, typically prevails low to very low permeability. Therefore, the piezometric level depth is generally very low (less than 10 meters). Groundwater flows through the fracture network, which is very irregularly distributed. Spring flow rates are usually very low, less than 1 L/s, most of springs remaining dry during the dry periods. Groundwater in hard rocks shows low mineralisation and a calcium-bicarbonate (occasionally magnesium-bicarbonate) composition. From a regional point of view, the Vicort and Algairén ranges are the main recharge areas for their adjacent aquifer units.

INTRODUCTION

The studied zone spans the Algairén and Vicort ranges, located in the Iberian Range (NE of Spain) between the Jalón and Huerva rivers, two tributaries to the Ebro River by its right margin. The study area is near 638 km^2. The Palaeozoic rocks of the area consist of shales, sandstones and quartzites which form two big, parallel mountain ranges, the Algairén range (its highest peak being 1,275 m above the sea level) and the Vicort range (1,411 m).

All previous regional hydrogeological studies have considered these Palaeozoic outcrops as impervious materials dividing two important hydrogeological units (aquifers): the "Campo de Cariñena" to the NE (Authority Water 1999) and the "Depresión de Calatayud" to the SW, the boundaries of both being placed along the Algairén and Vicort watersheds.

The aim of this paper is to re-define the hydrogeological units of the area incorporating the Palaeozoic outcrops, and to establish a model of hydrological behaviour of these materials and their relationships to surrounding aquifers.

GEOLOGICAL DESCRIPTION

The outcrops of the study area are dominated by Lower Cambrian and lower Ordovician sedimentary rocks with few Precambrian metasedimentary rocks and a small outcrop of Permian volcanic rocks (rhyo-dacites). Additionally, some Mesozoic carbonate rocks as well as Tertiary and Quaternary detrital deposits are present.

The Precambrian Paracuellos Group crop out in the study area close to the villages of El Frasno and Codos. It is composed of schist and little sandstone. Cambrian rocks are exposed SW of the Grío River in NW-SE trending outcrops. The base of the Lower Cambrian is represented by the 400 m thick Bámbola Formation, composed of white quartzite, with some sandstone and microconglomerate. The overlying, 300 m thick Embid Formation crops out extensively on the Vicort range and is composed of sandstones and shales. The rest of the Lower Cambrian units (Jalón, Ribota and Huérmeda formations) sum up ca. 300 m in thickness and are exposed in small outcrops of shale, sandstone, dolostone and white to greenish quartzite. Lower Ordovician (Tremadocian and Arenigian) rocks are exposed NE of the Grío River. Quartzite, shale and sandstone of the Borrachón, Dere, Santed and Armorican Quartzite formations sum up 1,800 m in thickness.

The Cambrian and Ordovician outcrops are separated by an important reverse fault, the Datos fault, which runs throughout the outcrops of the Precambrian Paracuellos Group and is covered by Quaternary gravel, silt and clay. At present, the Grío River follows the course of the fault.

"RÍO GRÍO-FOCES DEL JALÓN" HYDROGEOLOGICAL UNIT

For the present work, an exhaustive water point inventory has been completed, 19 springs, 46 wells have been traced. The latter are placed on the alluvial aquifer of the Grío River.

The hydrogeological interest of this unit focuses on the Palaeozoic quartzitic rocks (Bámbola Quartzite and Armorican Quartzite formations), which show high values of hydraulic conductivity because of the high permeability due to fractures. Recharge is produced by rainfall infiltration and by infiltration from streams flowing through the quartzites, as can be observed in the tunnels excavated for the High Velocity Train (AVE). Quartzite gives place to excellent fissured aquifers because its geomechanic behaviour. Fracture nets produced within this fine-grained, hard rock are clean and favour the circulation of groundwater.

In the study area, there are also detrital deposits with high interstice permeability, as the Tertiary deposits located both to the N (Detrital Tertiary and Pliocene-Quaternary alluvium of Alfamén aquifer) and to the S (Tertiary conglomerates and alluvium of the Perejiles River) of this Hydrogeological Unit. Finally it is worth to note the existence of an alluvial aquifer associated to the Grío River, between the villages of Codos and Tobed.

Cross section on fig.2 illustrates the proposed behaviour model for the Hydrogeological Unit defined herein in relation to the two adjacent units. The section runs SW-NE, i.e. perpendicular to the main structures of the Iberian Range (NW-SE trend). The model also indicates the existence of a fissure flow within the quartzitic formations, parallel to the general tectonic structures and perpendicular to the main flow shown on the cross section.

Drainage divide for surface runoff mostly coincides with that for underground flow, defining a twofold drainage toward the interior of the Unit (Grío River) and toward external aquifers.

Inner drainage of the Unit

It accounts for underground water that infiltrates in this Hydrogeological Unit and discharges within. The ranges of Vicort and Algairén are important recharge areas for these underground flows.

Discharge occurs mainly throughout the Grío River tracing the Datos fault, which works as a general collector for fissure circulation. Fig.1 shows the behaviour of the Datos fault collecting underground flows from the intersecting fissure net.

The Grío River alluvial aquifer is located, between Codos and Tobed, atop the Datos fault and is fed by water flowing throughout the fault. At the same time, the aquifer is drained by the Grío River which undergoes a noticeable flow increase along its low course, as is shown on fig.1. The weak mineralisation of

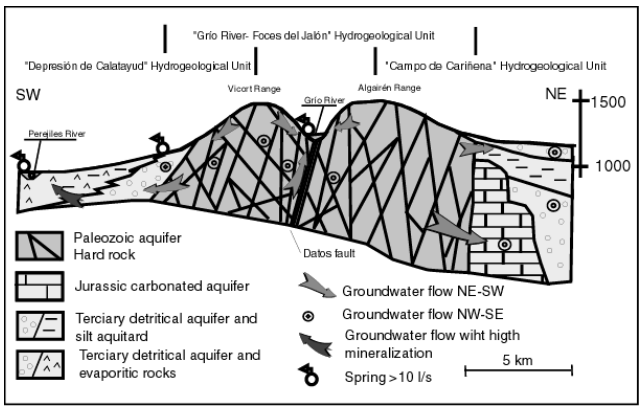

Figure 1. Hydrogeological cross-section of Vicort Range

water from quartzite aquifers renders a notable dilution of Grío River water (see fig.2).

Underground flow along the Vicort range discharges on the westernmost part of this massif, directly to the stream of the Jalón River, which run sharply through the range at an altitude of 450 m. The discharge of such parallel flow is demonstrated by the hydrochemical profile performed along the Jalón (Fig.2), which reveals the strong dilution induced by water from Palaeozoic aquifers. Springs flowing from the bottom of the Jalón stream are barely manifested due to their small flow rates. Recently, a tunnel six-kilometres long has been perforated through the range at an altitude close to that of the Jalón River, draining water at a continuous flow rate over 10 L/s.

External drainage of the Unit.

The quartzitic Palaeozoic aquifers do also drain towards the outer margin of the Unit, providing underground recharge to nearby hydrogeological units.

To the NE, they feed directly the Jurassic carbonates, Detrital Tertiary deposits of Alfamén and Pliocene-Quaternary alluvium of Alfamén aquifers, all belonging to the "Campo de Cariñena" Hydrogeological Unit. An hydrogeological cross-section of the boundary between the two units is shown on fig.1. It is noteworthy that water supplies to all villages located along the boundary zone are taken from wells drilled in Palaeozoic rocks.

To the SW, the quartzitic Palaeozoic aquifers feed directly the Tertiary conglomerates aquifer through the boundary with the "Depresión de Calatayud" Hydrogeological Unit. Groundwater flowing through the latter aquifer encounters the central, evaporitic (gypsum) facies of the Calatayud basin, producing the springs of Langa, Ruesca, Orera and Sediles, which amount over 100 L/s altogether. The altitude of these springs is 750 m, the same as the flowing borehole at Güemil. A part of the underground flow progress further to the W through the Tertiary conglomerates and discharges at a rate of 5 L/s in the spring of Huérmeda, near the Jalón River.

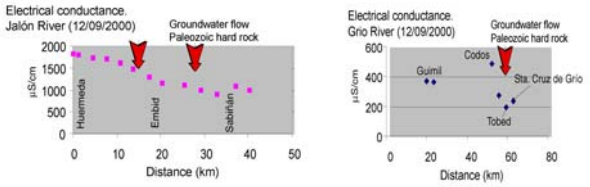

Figure 2. Evolution of electrical conductance (µS/cm) in Grío and Jalon rivers

CONCLUSIONS

The Palaeozoic, quartzitic hard rocks building the ranges of Vicort and Algairén have a remarkable fissure permeability forming aquifers of great interest for water supply to villages, maintenance of river flows and underground feeding to nearby, detrital and carbonate aquifers belonging to official, formerly established hydrogeological units.

Considered as impervious, hitherto the bulk of Palaeozoic hard rocks has not been included in any hydrogeological unit. In base of inventory data and observations on their hydraulic behaviour, we include the Palaeozoic materials of the Vicort and Algairén ranges within the "río Grío-Foces del Jalón" Hydrogeological Unit, proposed herein.

Drainage of quartzitic aquifers occurs both inside the Unit and towards the aquifers of nearby hydrogeological units. The most important springs are located atop major faults that collect water from the intersecting fissure net, and also in Tertiary-Quaternary detrital deposits that also work as collectors for fissure systems.

Assessing underground water resources from Palaeozoic quartzitic aquifers is a quite difficult task, given the scattered pattern of discharges and, especially, the drainage towards nearby aquifers.

Acknowledgements

This work has been carried out in the framework of the Project LOWRGREP (Landscape-use Optimization With regards of the Groundwater Resources Protection in the mountain hardrock areas) financed by European funds.

REFERENCES

IGME (1989) Estudio hidrogeológico para el abastecimiento de la localidad de Tobed (Zaragoza) (In Spanish. Unpublished)

MOPT (1990) Viability study of artificial recharge in the detrital aquifer of Alfamén (In Spanish. Unpublished)

MOPT (1991) Viability study of the Mularroya dam in the Grío River, villages of La Almunia and others (Zaragoza)" (In Spanish. Unpublished)

Authority Water (1999) Delimitation of Hydrogeological Units from the Ebro Basin (Unpublished)

Hydrogeologic properties of deep fractured aquifers in Germany: new data from long-term pumping tests in the Bruchsal geothermal wells and the KTB well at Oberpfalz

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A b s t r a c t : The two geothermal wells at Bruchsal are located at the margin of the Upper Rhine Graben, SW-Germany. The temperature of the aquifer is 135 °C. In 2002 a several months lasting circulation test with a rate of 20 L/s was performed. Well head temperature was about 107 °C. Transmissivity of the Buntsandstein-Permian aquifer is $T = 8 \times 10^{-5}$ m^2/s and TDS of the circulated fluid is 127 g/L with chlorid and sodium as the main components. Another one-year lasting pumping test in crystalline basement rocks was carried out at the KTB site in central Germany. The pumping rate started with 30 L/min during the first months, later the rate was doubled. Transmissivity of the aquifer is on the order of $T = 9.5 \times 10^{-6}$ m^2/s. TDS of the fluid is 62 g/L with chloride, calcium and sodium as the main components.

Figure 1. Location of the wells at Bruchsal and KTB

Two geothermal wells at Bruchsal (fig.1), southwest Germany, are located at the margin of the Upper Rhine Graben, a major Tertiary rift structure in Variscan continental crust. The geothermal wells were drilled into the Buntsandstein-Permian aquifer to the depths of 1,870 m (GB1) and 2,550 m (GB2). The lateral distance between the wells is about 1.5 km. The aim was to construct a geothermal doublet by injecting cold-water into one well (GB1) and extracting hot-water from the aquifer at the other well (GB2). The temperature of the aquifer is 135 °C. During summer and autumn 2002, a circulation test lasting several months with a circulation rate of 19–22 L/s was performed. During this test, the temperature at the well head was about 107 °C. Under in situ conditions, transmissivity of the aquifer at GB2 is on the order of $T = 8 \times 10^{-5}$ m^2/s. Pressure reduction at the end of the test indicating probably reservoir boundaries (fig.2).

The circulated fluid had the character of a brine, with a measured TDS content of 127 g/L with chloride (75.5 g/L) and sodium (37.5 g/L) as the main components (fig.3). Water at the wellhead appears to be slightly oversaturated with respect to calcite and quartz and undersaturated with respect to gypsum. Following temperature reduction for geothermal purposes, increasing saturation indices for quartz and decreasing indices for calcite and gypsum are expected. At the bottom of the injection well precipitations of lead, arsenic, and iron containing substances were detected matching very well to thermodynamic calculations of the fluid.

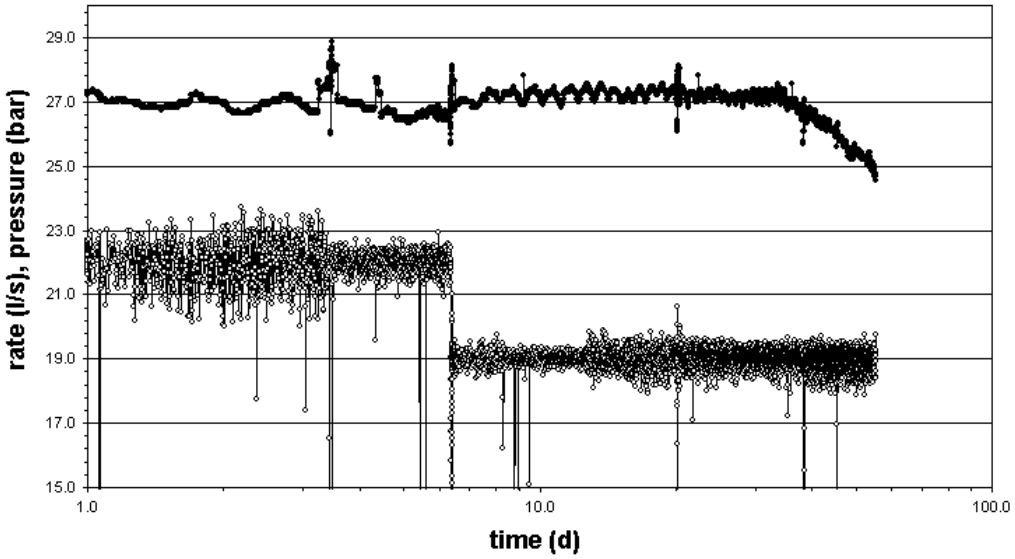

Figure 2. Geothermal test: extraction of hot water (107˚C) with a rate of 19-22 L/s out of the well Bruchsal GB2

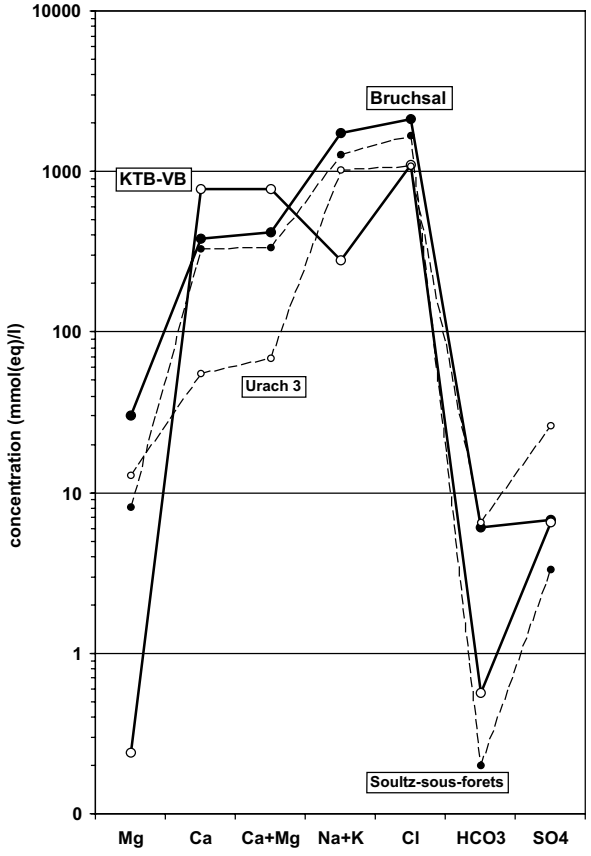

Figure 3. Hydrochemical properties of the Bruchsal- and KTB-VB-fluid, compared with other typical deep crystalline fluids

At the KTB site at Oberpfalz, central Germany, two deep boreholes were drilled; a 4,000 m deep pilot hole (VB) and a 9,100 m deep main hole (HB). The boreholes are located within about 200 m of each other and are drilled into paragneisses and metabasites. The KTB-VB borehole is cased down to 3850 m (open hole: 3850-4000 m). A production test at KTB-VB commenced in June 2002 and will continue through until June 2003. During the first phase of this test, water at a rate of about 30 l/min was continuously pumped from the borehole. Later, the rate increased up to 57 L/min. Drawdown (pressure), rate, temperature, pH, Eh and conductivity were measured continuously, and water samples were also continuously taken. Under in situ conditions, transmissivity of the aquifer at KTB-VB is on the order of $T = 9.5 \times 10^{-6}$ m^2/s (fig.4) and is much higher than years before.

The pumped fluid had a TDS content of 62 g/L with calcium (16 g/L), sodium (6.3 g/L) and chloride (37 g/L) as the main components (fig.3). Astonishingly, the fluid contains common trace elements of natural waters at extremely low concentration levels. As, Al, Cr, Be, Co, Zn, Pb, Cd and others were not detectable. As yet the composition of the fluid remained constant during the pumping test. The pH-value of 5.4 was calculated using the temperature dependence of Kw. Saturation states of the fluids were compared using this pH-value and the bottom hole temperature of 120˚C. The KTB fluid is slightly oversaturated with respect to anhydrite, barite, celestite and fluorite. It is close to saturation with respect to quartz and calcite.

We compared the KTB-fluid with other deep fluids in crystalline basement rocks like the fluid from the Urach 3 well in SW-Germany (depth: 4444 m) and Soultz-sous-Forêts near Bruchsal (depth: 5000 m). The main components of all these fluids are typically Na and Cl (fig.3). The KTB-fluid is totally different from other water samples from the Variscian crust in Central Europe. Additionally the fluids in deep crystalline basement rocks in SW-Germany are CO_2-rich while the KTB-fluid is rich in CH_4 and N_2. Composition patterns similiar to that of KTB were reported from some locations on the "cold" Canadian shield (Eye-Dashwa, Lake du Bonnet 2). The Cl/Br-ration from KTB suggest a fluid resulting from most intensive water rock interaction.

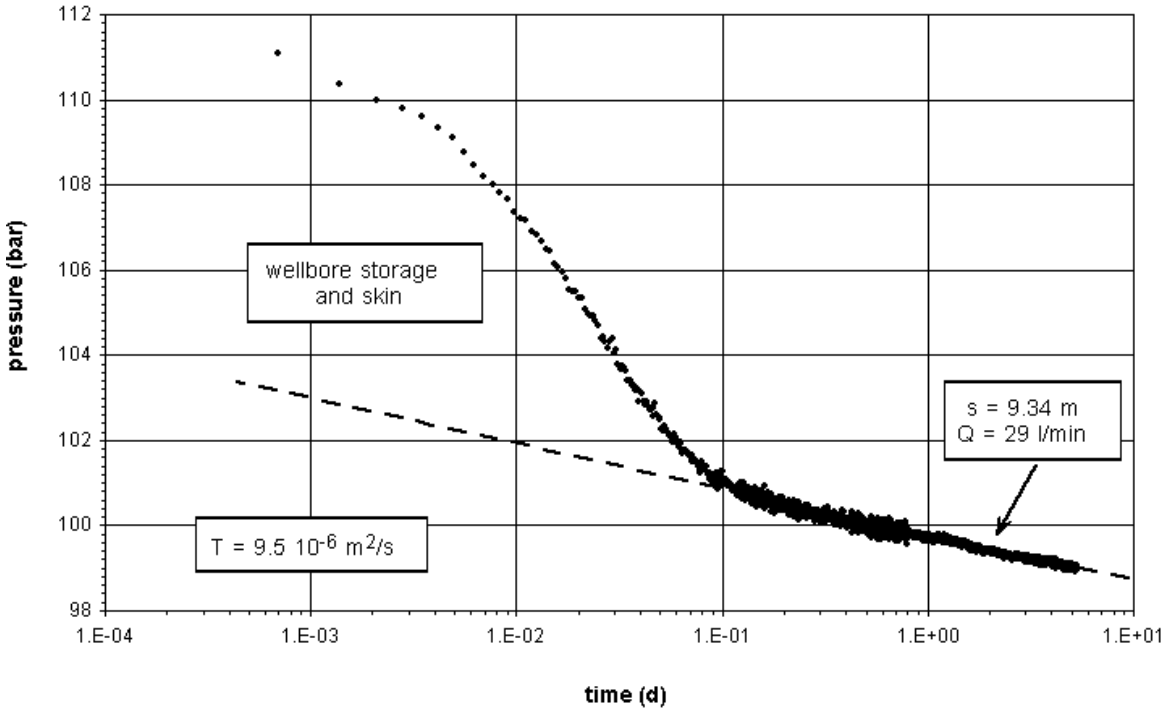

Figure 4. Long-term pumping test in KTB-VB

Groundwater in fractured rocks of the Kopaonik Massif in the Republic of Serbia

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A b s t r a c t : Central massif in Serbia is distinctive of the mountain Kopaonik that occupies a middle part of the Republic of Serbia. This mountain is famous for its beauties. All the same, it is famous for its karst springs rich with pure water. The task of this paper is to present general geological-hydrogeological properties of the terrain and physical-chemical properties of the waters from karst springs that can be utilized for municipal water supply as well as for bottling. These springs are bound to carbonated aquifers. Because of their dynamic reserves, they stand for significant natural resources and are situated in ecologically preserved area.

INTRODUCTION

Kopaonik is the biggest and one of the most beautiful mountains in Serbia. Because of its beauties, specific animal and plant populations, it was acclaimed the national park of Serbia. All the same, it is one of the greatest tourist centres in Serbia. As for its morphology, it is a high mountainous area with distinguished dissection of the terrain and fine texture of the relief. The highest peak is Pancic`s peak (2017 m.a.s.l.). Besides, Kopaonik is significant regarding occurrences and deposits of various resources, natural, mineral, and thermal waters that represent high potentiality for the market of the Republic of Serbia.

GENERAL GEOLOGIC-HYDROGEOLOGICAL PROPERTIES OF THE TERRAIN

The region of Kopaonik distinguishes with a compound geologic structure of the terrain and compound tectonic relations within the realms of this complex. Its geologic structure contains formations from Paleozoic, Mesozoic and Tertiary. Paleozoic rock complex consists of series of phyllite and graphite rocks, amphibolites, sericite schists and sandstones as well as of marbles, micaschists and gneisses. Mesozoic is represented by limestone, dolomite, diabase-cherty formations, diabase, spilite, and other formations. Tertiary rock complex is represented by volcanogenic sedimentary series (fig.1).

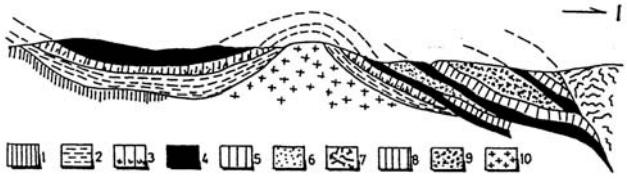

Figure 1. Tectonic profile of Kopaonik area after Grubic

Such a compound litostratigraphic rock complex conditioned complex hydrogeological relations within this massif. In accordance with a distinct hydrogeological function of mentioned rock complex, generally distinguish two types of rock masses: water permeable, and water impermeable rocks. From the aspect of ground water accumulating, the most significant is carbonate rock complex from Paleozoic and Mesozoic, where the karst aquifer occurs. It is significantly presented in marble and marbly limestone of Paleozoic that stretches along northwest and northeast rims of the massif. The aquifer represents an open hydrogeological structure. This allows precipitations to recharge intensively into waterbearing layer. In such cases, the zone of recharge coincides with the extension of the aquifer.

SPRINGS AND THEIR OCCURRENCES

The most intensive occurrences of the effluence of groundwaters of Kopaonik central massif are linked to marble and marbly limestone from Paleozoic. Overall, complex distinguishes with dissolution porosity caused by the process of karstification, which gives it a good accumulative capacity. Non-karst complex made of formations of schist, diabase-cherty formation and serpentinite contribute to good retardation capacity of the mentioned complex. As the rocks with low water permeability, they form impermeable underlying bed of the waterbearing carbonate layer. Natural resources of the karst aquifer are mostly formed on account of precipitations and direct infiltration of the waters that run into marble and marbly limestone as well as of water recharge from non-karst parts of the terrain.

It is estimated that aquifer is recharged by 5.3×10^6 m^3 of water from karst part of the terrain, gross area 11.2×10^6 m^2, and by 3.4×10^6 m^3 of water from non-karst part of the terrain, gross area 10.3×10^6 m^2, which amounts to 8.7×10^6 m^3 as a total recharge. The aquifer discharges by concentrated effluence of groundwater through springs that appear on the rim of the massif. Most of springs are of gravitational type and their appearances are linked to some of faults that represent preferential paths of groundwater flow. Springs are located in altitudes ranging from 1100 to 1500 m a.s.l. The yield of springs is variable and depends on the intensity of precipitation. This evident correlation exists during the whole hydrological year. Surface flow almost does not appear over such a fractured rock complex. Minimum yield of springs amounts to 5 – 50 L/s and maximum to 15 – 220 L/s.

PHYSICAL – CHEMICAL PROPERTIES OF KARST SPRING WATERS

Waters from karst springs of Kopaonik`s massif are of good quality and as such they are suitable for exploitation. They can be used for municipal water supply of the settlements at the foot of the mountain. Because of their beneficial physical – chemical properties and low mineralization (< 200 mg/L), they are suitable for bottling as table waters. Carbonate compound of basic rock mass, in this case marble and marbly limestone, contribute to their stable chemical composition. As for physical properties these waters are without colour, smell and taste, they are pellucid and do not puddle even during the strong rainfalls. They have stable temperature ranging between 7 and 9 °C and pH 7.0 to 7.4, which gives them neutral character. According to temperature values, they belong to cold waters. According to hardness they range from 6.2 to 6.5 °dH (after Clut), i.e. they belong to soft waters.

According to chemical composition, i.e. concentration of the anions and cations, waters from these springs belong to bicarbonate class – calcium group (after Alekin). Such a relation is in accordance with the properties of geological formations that build the aquifer. The results of biological analyses also approve the quality of these waters and they can be regarded as first class waters.

CONCLUSION

By their quality and quantity karst springs of Kopaonik`s massif represent natural resources of great significance. They are located in ecologically preserved environment. The whole area was declared The National Park of the Republic of Serbia. Water potentiality of these springs is still poorly developed. By their dynamic reserves and the way of their recharge, these springs can contribute to solving the problem of regional water supply. Therefore, the protection and preservation of these natural goods must be paid adequate attention along with the control of all urban projects, which are to be realised in the area.

REFERENCES

Stojadinovic D (2002) Water Potentiality of the Basins of the Rasina and the part of the West Morava, Belgrade

Filipovic B, Krunic O (1995) Hydrogeological Distinctions of Kopaonik. Symposium Geology and Mettallogeny of Kopaonik Mt, Kopaonik Yugoslavia

Vucetic N, Djokic I, Simic M, Papic P (1997) Conditions and possibilities of Using Karstified Limestone Aquifers in the Area of Brus Municipality. 100 Years of Hydrogeology in Yugoslavia, Belgrade

Correlation of hydrogeologic and tectonic characteristics of the hardrock aquifers in Tinos Island, Hellas

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A b s t r a c t : The apparition of the main groups of springs of a schist aquifer in Tinos Island is described, related to the tectonic regime of the island and of the spring's environment. The geological and geomorphologic conditions are examined connected to the faults and main ruptures. The comparison of the orientation of the given extended discontinuities with the orientation of the spring's emergencies, completed with different additional information, explain the alimentation and operation framework of the main springs groups. In the case of Tsiknias group, there is a coincidence of the above orientations and the extended discontinuities represent the main discharge flow paths, while in the case of Zodemeni group, these discontinuities represent the main draining collectors of the groundwater, leaving the discharge flow paths role to minor discontinuities.

GEOLOGICAL, TECTONIC AND GEOMORHOLOGICAL CONDITIONS

Tinos Island is mainly composed by the metamorphic system of the Cyclades. The lower sequence is constituted by marbles with alternations of gneiss and gneissic schist and typical schist. The upper one is composed by tectonically placed green schist and ophicalcite with the complex of ophiolite and gabbros. Eruptive rocks are encountered under the form of granite, granodiorite, diorite of Miocene, with some volcanic rocks. The post-alpine

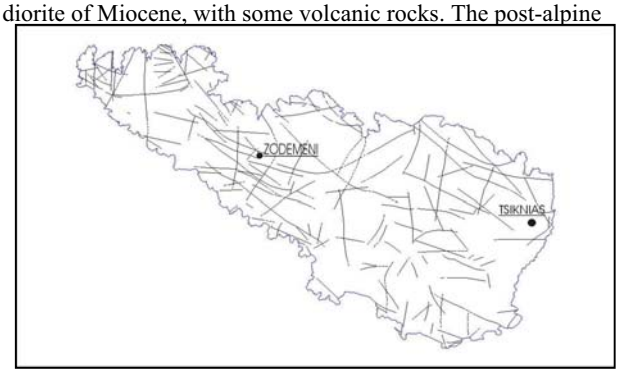

Figure 1. Map of the main faults in Tinos Island

formations complete the geological configuration, represented by Neogene and Quaternary deposits. A single anticline structure forms the tectonic regime of the island, with an axe of direction

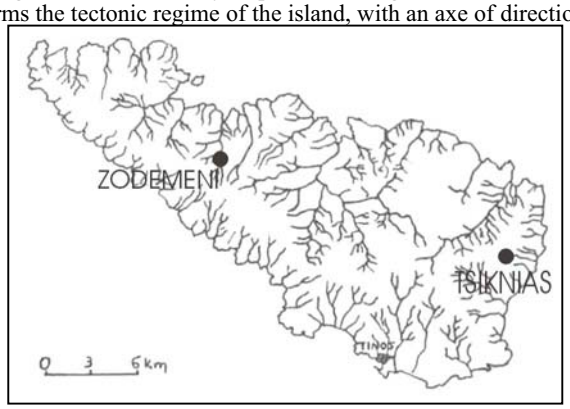

Figure 2. Drainage network of Tinos Island (Alexouli *et al.* 1977)

NW-SE and a plunge to the NE, parallel to the main watershed. The main watershed of the island is situated very close to the SW coasts. It is obvious, hence, that the majority of the runoff is oriented to the bigger sector with 3rd and 4th order channels, while the channels of the SW sector represent 1st and 2nd order, according Horton classification. The given differentiation supports the infiltration and the alimentation of the water tables. The later is also related to the leveling surfaces at the vicinity of the watershed, which helps with the relatively slow runoff, hence, the better infiltration conditions (another remarkable leveling surface corresponds to the triangular granitic outcrops). The trellis rectangular shape of the hydrographic network completes the favorite conditions for the Zodemeni group of springs.

THE SPRINGS OF THE ISLAND

The totality of the schistolithic environment springs of Tinos is located within the valleys. In the same valleys, the limited greenery of the island and the villages are also, normally, located. Each valley is a zone of a certain width at both sides of the axis, where the schist is tectonized in a more intensive way, forming a typical discontinuous media The schist presents here a more dense and deep system of ruptures, forming a typical discontinuous media for the groundwater accumulation and circulation. Additionally, the alteration is more intensive, thus a considerable superficial layer is formed, representing a porous media, directly connected with the beneath hardrock aquifer. Although the limited surface of the island many springs occur, with interesting discharge rates for the scale and the geological

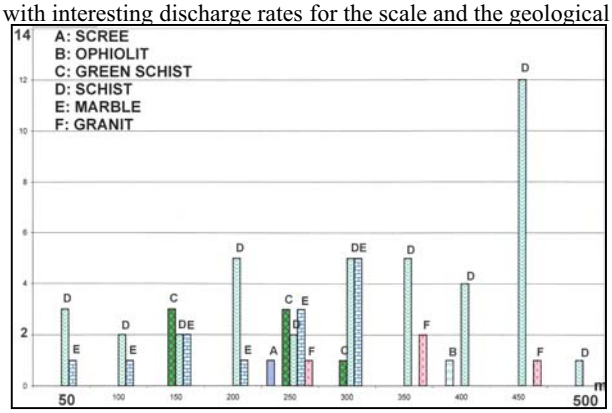

Figure 3. No of springs versus the geological formation and the elevation

configuration of the island. Additionally to the factors representing the geomorhologic setting (orientation of the hydrologic network, leveling surfaces), previously described, and the tectonic regime, the erosivity of the island is another important reason. According relevant study, the larger part of the island belongs to the category of medium erosivity. The latter is characterized either by a small thickness of weathered mantle in slopes, or by great thickness of weathered material in low

gradient slopes. All the springs emerging at the outcrops of schist complex are favoured by the above fact, in correlation with the geomorphologic and tectonic conditions.

Correlation concerning the totality of the springs

Despite the general rule, the number of springs increases with the elevation. This is more obvious and evident considering the metamorphic and ophiolitic system, because of successive local tectonic events. It is very important that the Zodemeni spring, being the most important spring in Tinos, is manifested at high elevation point.

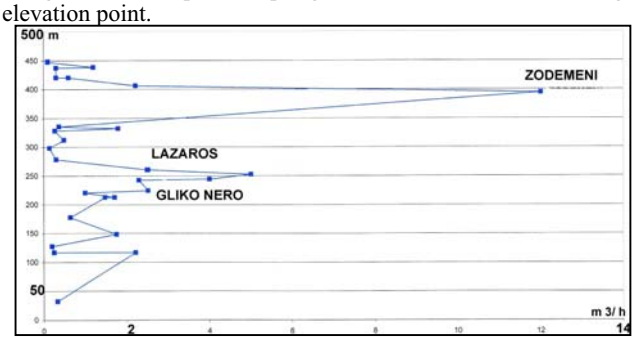

Figure 4. Discharge rate of springs of the humid period versus the elevation

As it is clearly observed, there is no any remarkable correlation connecting the discharge rate and the elevation of the springs. This is due to the fact that the springs belong and represent different partial aquifers, eventually participating to the same major aquatic system, but maintaining nevertheless an individual hydraulic behaviour.

The most interesting groups of springs

The Tsiknias springs

The aquifer of these springs is the system of green schist (relatively permeable sequence) and ophiolitic formations (relatively less permeable sequence), tectonically placed on the lower unit consisted of typical schist. The main fault system is directed almost to the N-S, with faults of considerable length, while the secondary system is the conjugate of the first one, with smaller faults of an E-W direction. Special interest is given to the normal fault at the northern part of the Glyky Nero area. Concerning the tectonic features of the schist, at the NW part of Tsiknias Mountain, the deep is in the N 60o to the SE and in the S, 30o to the NW. On the contrary, at the SE part the deep is 25o to the NW. Thus, at the east of the watershed of the mountain, a syncline axe is formed, which helps in the frame of the concentration of the groundwater.

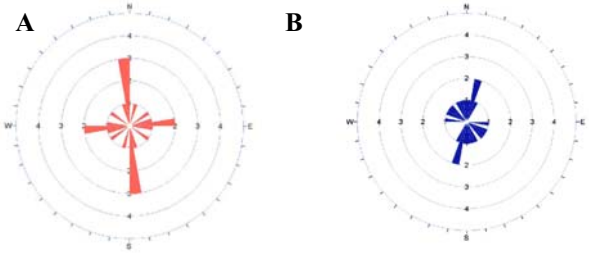

Figure 5. Rose diagrams of Tsiknias area. A: direction of faults, B: orientation of springs

The most important springs of the discussed group are the springs of *Glyky Nero*, *Lazaros* and *Akeratos*. According the rose diagram, the majority of the springs is discharged at the SE mountainside (from NW to SE). The exception is the springs of Akeratos but it belongs to another part of Tsiknias Mountain, separated by an extended col. The coincidence of the tectonic and the spring's orientation in the rose diagram verifies the role of the ruptures as discharge flow paths.

The Zodemeni springs

As it is clear from the rose diagram, the main fault system is oriented from NW to SE, which is the same orientation with the main watershed. The secondary fault system, of an orientation NNE-SSW, is the conjugate of the previous one and coincides with the principal directions of the valleys. An anticline structure, almost along the watershed, is oriented from NW to SE. The Zodemeni spring is the most important in Tinos Island, with a discharge rate 12-20 m3/h. At the upper part of the spring, an important plateau is formed, belonging to the levelling surfaces, characterized by very soft slopes, supporting the infiltration. The schistosity of the aquifer coincides to the groundwater flow to the emergence point. Within the plateau, a dense accumulation of Quartz veins is encountered, which favours the infiltration because of the intensive fracturation of the rock. The important discharge of the spring is related to the main fault NW-SE, intersected with the other faults and forming an important water table. Contrary to the Tsiknias springs, the main faults, almost perpendicular to the orientation of the emergence points, drain the aquifer and the transmission of the water to the emergence points is accomplished by the secondary faults. This aspect results to a better circulation and regularization of the groundwater. The trellis rectangular shape of the hydrographical network completes the favourite conditions for the Zodemeni group of springs.

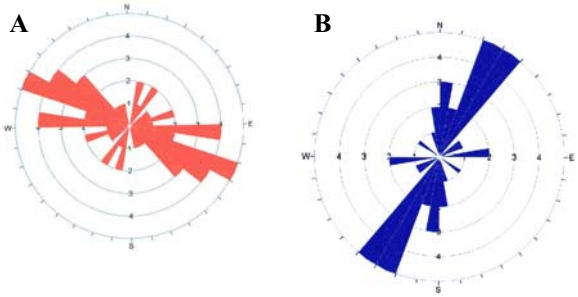

Figure 6. Rose diagrams of Zodemeni area. A: direction of faults, B: orientation of springs

REFERENCES

Alexouli-Livaditi A (1997) Geomorphological investigations of the drainage network and calculation of the peak runoff storm (Qp) of the main drainage basins of Tinos Island. Proc. Intern. Symp. Engineering Geology and Environment, Athens. In Marinos P, Koukis G, Tsiambaos G, Stournaras G (eds), p 19-24, Balkema

Alexouli-Livaditi A, Livaditis G (1997) Investigation and delineation of areas where intense erosion and mass wasting may occur at Tinos Island, Greece. Proc Intern Symp Engineering Geology and Environment, Athens. In Marinos P, Koukis G, Tsiambaos G, Stournaras G (eds), p 19-24, Balkema

Livaditis G, AlexouliI-Livaditi A (2001) The morphology of the Tinos Island. Bull Geol Soc of Greece. 34(1):389-396 (in Greek)

Melidonis MG (1980) The geology of Greece: the geological structure and mineral deposits of Tinos Island (Cyclades, Greece). Inst Geol Min Explor, Athens 13:859-874

Stournaras G, Alexiadou MCh, Koutsi R, Athitaki Th (2002) Main characteristics of the schist aquifers in Tinos Island (Aegean Sea, Hellas). Proc 1st Workshop IAH Hardock Hydrology WG, MEM WG, Tinos (in print)

Groundwater in fractured rocks of the Karelian Region (NW Russia) and Estonia

Ylo SYSTRA

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A b s t r a c t : Precambrian rocks of Karelia have insignificant porosity and are covered by Quaternary deposits. There is only one groundwater aquifer system, in fractured bedrock within fault zones and in soft sediments. Water is of good quality and extremely fresh, with total dissolved salt contents less than 100 mg/L. Bedrock chemistry clearly influences water composition; sulphide-rich basalt is associated with historically famous iron-rich mineral springs, while uranium-rich bedrock correlates with elevated radon in groundwater. Studied spring-water may be taken as a standard for natural clean groundwater. In Estonia Precambrian basement is buried under 100-700 m thick Vendian-Devonian sedimentary cover, which dips gently south (at 2-4 m per 1 km). There are four aquifer systems in sandstones and two aquifer systems in carbonaceous rock. Fractured zones facilitate maintain recharge of all aquifers from the Pandivere Upland. In strongly jointed rocks water flows faster, but can be easily be polluted. The major aquifers have good-quality drinking water, although concentrations of Fe, Ni, Ba, B and F ions are sometimes high.

KARELIAN REGION

The Karelian Region occupies an area of about 250 000 km^2 in the eastern part of the Fennoscandian Shield, composed of multiply deformed Archean and Proterozoic metamorphic and intrusive rocks. Bedrocks is overlain by Quaternary cover, usually up to 3-8 m in thickness, although crystalline rocks are extensively exposed along much of the shorelines of the White Sea, Lakes Ladoga and Onega. Thicker surficial deposits blanket ancient valleys, mostly formed along the fractured fault zones, and in glaciofluvial formations such as eskers, ice-river deltas and sanders (Geologia Karelii 1987).

Groundwater in bedrock and Quaternary deposits

Precambrian rocks are mostly massive, impermeable and do not contain groundwater. Where weathered however, some crystalline rocks exhibit low levels of secondary porosity. A dense network of near-vertical fracture systems developed during prolonged and episodic crustal evolution and deformations of the shield after the Svecofennian orogeny 1.88 Ga ago. Fault zones divide the whole territory into blocks of diverse size. In their central parts the density of tectonic joints is low, less than 10 in any direction per 10 m of profile and joint density also decreases with depth. Joint are short, closed and rocks are relatively impermeable. In the fault zones rocks are intensively fractured and in the central part often represented by tectonic breccia, cemented with low-temperature metasomatic minerals: quartz, carbonates, iron hydroxides, epodote, clorite, pyrite etc. Along the margins of these zones the intensity of jointing is many times greater. Even 100-150 m from faults, the number of joints exceeds 200 per 10 m in any direction. Joints here are open and long, and are typically coated by thin zones of low-temperature minerals some mm in thickness. Prolonged weathering processes have penetrated to the deeper levels of fault zones, resulting in linear valleys with prominent negative relief. They are usually 50-200 m wide and 25-150 m, the main zones up to 1-2 km wide, 500-600 m deep and some hundred km long (Systra 1991). Often faults have scarps on one or both sides. Deep valleys and resistant blocks between them have generated the typical undulating topography of Karelia.

There is a single aquifer in the Quaternary deposits and in upper part of the jointed and fractured bedrock in region. The moraine cover on the top of hills is thin and it is sandy in composition, rainfall infiltrates into bedrock quickly and enriches the groundwater by interaction with many mineral components in mineralized joints of fractured rock. Flowpaths through the bedrock are short with a high rate of infiltration. Most of springs are located at the foot of the scarps; typical discharge rates are. 0,2-3 L/s. Along the scarps it is sometimes possible to find springs every 25-50 m. The deepest parts of fault zones are usually occupied by open water-bodies, and there are numerous subaquatic springs. The ability for groundwater in crystalline bedrock and sandy Quaternary sediments to self-purify are limited. As consequence, many rivers and lakes near settlements have pollution from agriculture, industry and local communities, many of which lack adequate waste treatment facilities. Most of the local population in the Karelian villages prefers to use springs for drinking water. The resources of good-quality groundwater in the fractured bedrock are very limited.

Composition and properties of groundwater in fractured zones

Analyzed samples were taken from springs in the Paanajärvi National Park, NW Karelia (Borodulina and Systra 2001). This area is in pristine condition and there are no major industries within 300 km of the national park, created in 1992. The only source of pollutants is airborne transport from Western Europe, with the prevailing wind direction being from the SW. Spring-water discharges at temperature +3,5-5,0º C. During the short infiltration the water stays ultra-fresh, their total dissolved solids (TDS) being less than 100 mg/L. Water is highly saturated with oxygen (7.1-8.7 mg/L, corresponding to ca 56-69 % saturation) and are hydro-carbonaceous-calcium waters in composition (tab.1, No 1-3).

Although the global transport of mineral salts occurs in Estonia it is calculated that average precipitation is 23 mg/L (Raukas and Teedumäe 1997), the main sources of the dissolved solids in Estonia are in the bedrock, whereas in Karelia mostly fractured rocks of fault zones. This is clearly reflected in trace element groundwater geochemistry in bedrock (tab.1). The influence of bedrock composition on groundwater is also evident when compaing analyses. At Paanajärvi the springs discharges from basalt (tab.1, No 1), andesitic basalt (No 2) and quartz porphyry (No 3), and at Kilpisjärvi (Saana Strict Reserve) from fractured clayey slates, quartzite and dolomites (No 4).

Early Proterozoic sedimentary-volcanic rocks and fault zones in Karelia locally host uranium mineralization and groundwater from wells and springs can show high radon concentrations. A very distinctive iron-rich mineral water, forms in association with iron- and sulfide- rich Jatulian basalts of the Onega synclinorium. The Russian Tsar Peter 1 established a mineral spa and sanitorium at these springs in 1719, and it continues to operate today.

Near the spring mires the diversity of vegetation is greater than in surrounding wetlands, since the spring waters are exceptionally rich in trace element nutrients. Groundwater feeds mire vegetation also along the fault zone under the peat layer.

ESTONIA

Estonia is located on the marginal zone of the Fennoscandian Shield. Crystalline basement is buried here under 125-500 m of Vendian-Paleozoic sedimentary cover. This is known as the Esto nian Homocline with layers of sedimentary rocks dipping to the south and southeast average 3 m per km (Raukas and Teedumäe 1997).

Table 1. Some of physical properties and concentrations of main ions in groundwater of Karelia, Finnish Kilpisjärvi and Estonia

No	A L/s	T ºC	pH	CO_2 mg/L	TDS mg/L	Na^+ mg/L	K^+ mg/L	Ca^{++} mg/L	Mg^{++} mg/L	NH_4^+ mg/L	HCO_3^- mg/L	Cl^- mg/L	SO_4^{--} mg/L	PO_4^{---} mg/L	NO_2^- mg/L	NO_3^- mg/L
1	0.5	3.5	7.39	8.2	72	1.4	1.1	13.7	2.2	0.01	43.4	0.7	5.5	0.03	0.01	0.04
2	0.2	5.4	6.33	44.5	43	1.3	0.1	7.1	1.1	0.01	23.3	0.7	6.6	0.01	0.01	0.04
3	0.3	-	6.76	41.1	95	1.9	1.1	20.3	1.5	0.01	62.0	0.7	5.8	0.02	0.01	0.01
4	0.2	2.5	-	-	-	2.36	1.17	14.3	5.85	-	-	1.37	22.8	<0.01	-	0.4
5	-	-	7.2	8.8	540	53.1	10.0	59.1	34.6	0.41	384.4	52.8	35.4	-	0.00	<0.1
6	-	-	7.5	39.6	204	2.3	3.5	41.1	18.2	0.02	189.1	11.0	20.7	-	0.00	<0.1

No	Si mg/L	F mg/L	Li µg/L	Al µg/L	Ti µg/L	Cr µg/L	V µg/L	Fe µg/L	Mn µg/L	Ni µg/L	Co µg/L	Cu µg/L	Zn µg/L	Ga µg/L	As µg/L	Se µg/L
1	3.7	0.13	0.80	8.9	0.74	0.53	0.61	59.0	0.93	0.25	0.04	0.54	77.5	0.18	0.03	0.92
2	3.0	0.07	0.10	52.5	0.64	0.10	0.08	39.8	3.08	0.25	0.05	0.25	16.3	0.15	0.06	0.28
3	3.2	0.19	0.59	68.0	3.47	0.90	0.31	128.0	4.81	0.25	0.09	0.63	33.4	0.21	0.05	0.10
4	3.01	<0.1	0.77	17.5	-	-	1.37	<0,03	0.02	0.02	0.06	0.99	1.94	-	0.08	<0.5
5	4.48	1.65	97	20	-	<1	-	1230	22	11	-	<1	6	-	<1	<0.2
6	3.87	0.28	2	<3	-	-	-	1160	<50	16	-	<1	<20	-	3	<0.2

No	Br µg/L	Sr µg/L	Rb µg/L	Mo µg/L	Cd µg/L	Sb µg/L	I µg/L	Ba µg/L	B µg/L	Ce µg/L	Nd µg/L	U µg/L	Pb µg/L	W µg/L	Hg µg/L
1	0.50	13.9	0.48	0.51	0.01	0.64	1.39	14.4	-	0.04	0.04	0.03	0.13	0.07	0.12
2	0.98	7.95	0.56	0.18	0.17	0.50	1.37	7.6	-	0.26	2.66	0.12	1.25	0.01	0.03
3	1.16	32.2	1.17	1.23	0.82	0.50	1.30	48.5	-	0.56	0.43	0.08	1.62	0.01	0.03
4	-	83.1	1.05	0.30	<0.02	0.02	-	49.6	2.33	-	-	0.23	0.02	-	-
5	-	-	-	5	<0.2	<50	<50	185	520	-	-	0.00039	<2	-	<0.05
6	-	-		5	<0.2	-	<100	739	<300	-	-	0,0000001	<0.2	-	<0.05

Legend: Places of groundwater sampling: No 1-3-springs in the Paanajärvi NP, Republic of Karelia, Russia (Borodulina and Systra, 2001). No 4-spring on the foot of the Saana Mountain, Kilpisjärvi, Finnish Lapland (Geolaboratory of the GSF, Helsinki). No 5-well in the Ordovician water horizon in Paide and No 6-well in the Middle-Lower-Devonian aquifer in Kilingi-Nõmme, Estonia (both Laboratory of the Geological Survey of Estonia, Tallinn). (-)-component is not studied.

Groundwater in Estonian bedrock

Groundwater in the crystalline basement is restricted to fractured zones and in weathered parts, it salt content is up to 22 g/L (Vingissaar 1978).

The Cambrian-Vendian and Ordovician-Cambrian aquifer complexes are the main sources of drinking water in northern Estonia, while the Middle Devonian and Middle-Lower-Devonian aquifer complexes are most important in southern Estonia. Weakly cemented porous sandstones form mostly confined aquifers, in which water yielding capacity is relatively high. Aquifer complexes and single layers are separated by aquitards, which mostly comprise clays in the Vendian and Cambrian rocks, and also marls in the Devonian sequences. Groundwater flows quicker and the capacity of wells is higher in sandstones, where they have intensive bedding jointing or are fractured in fault zones. In the scarps of South Estonia, water has washed out fine-grained sand from Devonian sandstones along the vertical tectonic joints. Numerous caves have formed in the sandstones, which are some meters high and wide, and some tens m long, their walls being angular according to the orientation of the main joint systems. Springs are often associated at the intersections between vertical and inclined joint systems in bedrock; discharge often exceeds 2-3 L/s.

The Silurian-Ordovician aquifer complex is an important source of water for Central Estonia. It consists of limestone and dolomite with clayey marl interbeds. The conductivity of water depends on vertical and horizontal joints, karst and fracturing also occur. The thickness of karstified and the weathered zone in the carbonate rocks is usually 1-3 m, sometimes 5-10 m, and exceptionally up to 75 m. Only 13 % of the total rock sequence comprises laterally extensive aquifers. These conductive permeable zones are separated from each other by 5-10 m thick layers, in which groundwater flows mainly in vertical direction in the fault zones. The depth of 75 m is considered as the lowest of sufficient water yielding layers of whole aquifer complex (Perens 1998).

Groundwater flow in Estonia

The total amount of groundwater in Estonia in fractured zones and rock pore spaces is nearly 2000 km^3 (Raukas and Teedumäe 1997). Faulting and fracturing is essential to maintain recharge of deep groundwater layers and aquifer complexes. The flow systems occur in uplands, where the groundwater table is more than 100 m, in southeast Estonia – 180-280 m above sea level. The groundwater head declines from the uplands, the difference of it in some aquitards being 50-60 m. At the base of slopes there are numerous springs sometimes with discharge 200-300 L/s.

Groundwater composition in Estonia

In the active exchange zone groundwater is of HCO_3-Ca-Mg or HCO_3-Mg-Ca type with TDS commonly 0.3-0.4 g/L, in the passive exchange zone – 0.3-1.5 g/L. In some places trace element abundances exceed recommended limits for drinking water, notably F, B in Silurian-Ordovician sequence of Estonia, and Ba, B, Ni, Fe in Devonian sandstones of South and Southeast Estonia (tab.1, No 5-6).

REFERENCES

Borodulina GS, Systra YJ (2001) Springs along the Asterva-järvi nature path in Paanajärvi National Park. Oulanka Reports, 25:5-8

Geologia Karelii (1987) Nauka, Leningrad, 231 pp (In Russian)

Perens R (1998) The hydrogeological map of Estonia at scale of 1:400 000. Explanatory note. Geol Survey, Tallinn, 40 pp

Raukas A, Teedumäe A (eds) (1997) Geology and mineral resources of Estonia. Eston Acad Publishers, Tallinn,436 pp

Systra YJ (1991) Tektonika Karel'skogo Regiona. Nauka, Sankt-Petersburg 176 pp (In Russian)

Vingissaar P (1978) Eesti mineraalveed ja nende kasutamine. In: Heinsalu Ü (ed.). Põhjavee kasutamisest ja kaitsest Eest NSV-s. ENSV TA, Tallinn: 54-71

Groundwater occurrence in fractured metamorphic rocks - quality and quantity: an example from North East Brazil

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A b s t r a c t : In the year 2002 in the administrative district of Petrolina, North East Brazil, 532 water samples were taken from production water wells. The aim of analysing the groundwater and evaluating quality versus quantity was the production of maps showing new ways to the water exploitation in the area. 299 wells are producing a reasonable quantity of water (>1m^3/h). Deep wells mainly have a poor quality and low production. The water quality and the highest production is with some exceptions linked to the shallow wells with up to 50 m depth. No importance can be seen in the tectonic features or in any special locality. In a few cases the alluvial sediments accumulate to over 20 m thickness shallow wells that have good production and good water quality.

STUDY AREA

The example was taken from the North East of Brazil in the far west of the Pernambuco state. The area, which was sampled, covers 5500 km^2 the administrative district of Petrolina limited in the South by the São Francisco river. Some part of the area is irrigated with water from this river. In the remaining part of the district some tens of subsurface dams and approximately 1000 water wells supply the poor farmland with water, mainly for domestic purposes, gardens with vegetables and the animals in general goats.

GEOLOGY

Crystalline rocks and different kind of metamorphic rocks of Archaican age which belong to the São Francisco Craton are forming the subsurface of the district. A few metamorphic rocks of Proterozoic age are mapped. Tertiary covers small areas and the outcrops show little thickness of the sediments. In the folded series also some marlstones can be found. In the valleys which are most of the time dry alluvial sediments are accumulated up to 5m to 10m. The thickness is often overestimated because of the weathered rock zone which is difficult to separate from the fine sediments of the river bed. From air photos paleo-valleys can be mapped. The sediment fill seems to be rather thin. The features are following paleo-structures and they are remarkable in the identification of water wells.

Large faults striking 45° are crossing the region while few faults strike with 165°. Some faults represent large shear zones but no evidence of recent remobilisation of the tectonic features can be observed. Fractures of little extension and fissures in small linked networks do not form an aquifer.

CLIMATE

The climate of the region is semiarid. The mean precipitation is 450 mm/a and the potential evapotranspiration is about 2500 mm/a. The distribution of the rainfall is irregular and some years have less than 100 mm during a few days. In other years the precipitation can reach 800 mm. The rain maximum in March is close to 140 mm/a. Between May and November rainfall is rare and noted only in some years. The mean temperature is 30°C. Creeks and small rivers in general are flowing during one or two months in the summer.

WATER WELLS

Water wells were constructed in different campaigns from the early sixties – a few – some in the eighties and mainly at the beginning of the nineties. From the more than thousand wells only the half is still in function. About 200 may be recovered after replacing the pump system. As there is no energy available the pumps are powered by wind.

The depth of the wells rages from 30 m to 100 m and the diameter is 6". In a few cases the diameter of the well is over one meter if they are built in alluvial material. The depth of the wells is not linked to the time they were constructed. Even in the early sixties wells with 100 m depth were drilled.

All wells have a short casing. Reaching the solid rock the wells are without well screen or additional casing. All fissures and fractures can contribute directly to the well. The drawdown reaches in some cases 80 m.

The wells are with some exceptions localized in the dry paleo-valleys or in the few significant shear and fault zones. The morphology was mainly the "leading guide" to the spot were the well was drilled. No geophysical method was used to the authors knowledge so far.

SAMPLING

During January to March 2002 a water sampling campaign was carried out in the administrative district of Petrolina. 532 water samples were taken from almost all operating wells. Hardness, electrical conductivity, pH, and Eh were analysed in the field. One sample for the anions and one for the cations was taken and conserved and sealed and later send by air freight to Berlin. These analyses were carried out at the laboratory at the Technische Universität Berlin.

As the sampling took place in the raining season groundwater was not pumped at all places. In cases were no wind was blowing the wind wheel was powered manually. As the diameter and the depth of the well was known, the calculated quantity of water of the well could be extracted three to four times to prevent any sampling of stagnant water.

RESULTS OF ANALYSIS

The results of the analysis do not show any groundwater type that is typical for the rock where the well is located. The only exception can be noted in the water from wells situated in crystalline carbonates. The calcium carbonate ions are not more abundant in these wells and the pH is of low alkalinity.

Electric conductivity and sodium chloride

The EC ranges in the samples from <1 mS up to >20 mS. 115 samples have less than 1 g/L of TDS and 208 less than 2 g/L. The chloride content ranges from 21 ppm to over 10000 ppm and the sodium content from 3 ppm to over 3600 ppm. The highly mineralised water derives with a few exceptions from deep wells. Fig.1 shows a Stiff diagram for deep and shallow groundwater.

The water is preferential a NaCl-type but from deep wells not always of this type is represented as shown in tab.1. The shallow wells are mainly little mineralised and

Schrober (1995) analysed in the deep wells of the crystalline of the Blackwood Forest the NaCl-type. As the wells are much deeper the separation of the heavier ions may take place.

Other cations

Calcium and magnesium are the cations of further interest. Both are ranging from 15 ppm to 1850 ppm for Calcium and 1700 for magnesium. In deep wells the dominance of both may exist and may help to a better interpretation. The problem is the missing of some data for the wells which were sampled to give a complete statistical result.

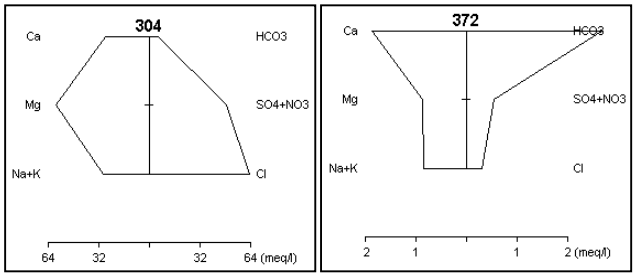

Figure 1. Stiff diagram from a deep well left and a shallow well right

WELL HYDRAULIC DATA

The most effective wells are up to 50 m deep. The deeper wells have a lean to bad quality and a bad specific yield. The draw down in wells with over 100 m depth reaches up to 80 m yielding 2 m^3/h. Wells located on clear marked structures or even on intersected structures yield little amounts of water. In the upthrust zones the mineralization of the water is high and the yield is lower than expected.

299 wells out of 634 produce over 1 m^3/h water each. 29 wells yield from 5 to 10 m^3/h and 5 wells yield over 10 m^3/h. The best well is situated in the weathered zone in a paleo-valley and yielded 35 m^3/h.

DISCUSSION

The question of the origin of the minerals in the groundwater is not clearly to answer. Gascoyne and Kaminani (1989) assumed that the origin might be from the rock matrix and crystal water. Hofmann and Tröger (1998) discussed the possibility of atmospheric origin of the minerals transported with the fine soil. Under the climatic conditions the evaporation of the water forces a salt residue on the top soil. The cations derived from the minerals which are forming the rock. The origin of the chloride is doubtful because it is normally not abundant in the rocks of the region. The explanation of Gascoyne and Kaminani (1989) may be the best.

CONCLUSIONS

The detailed study of the hard rock area of the municipal of Petrolina demonstrated that deep wells (>50 m) mainly have less yield than shallow wells and have a lower groundwater quality. Wells in tectonic structures yield less water than expected. The groundwater from this wells mainly has a lean to bad quality. The most effective wells are located in paleo-valleys in the weathered rock. The best conditions are found in places where the water circulation is high and the minerals are leached and transported away with the surface water.

REFERENCES

Adanu E (1989) Hydrogeology of the Basement Complex Terrain in the Zaria-Kaduna Area (Nigeria). Berliner Geowissenschaftliche Abhandlungen Reihe A, Band 113, 75 pp

Gascoyne M, Kamineni DC (1993) The Hydrogeochemistry of fractured plutonic rocks in the Canadian Shield. Applied Hydrogeology 2 – 2/1994:43-49

Hofmann T, Tröger U (1998) Hydrogeological basic survey in the region of Água Fria, Bahia, Brasil. Zbl Geol Paläont Teil 1, 1997(3-6):823 – 834

Mailu GM (1992) The Influence of precambrian metamorphic rocks on groundwater in the Chyulu Area, Kenya. Applied Hydrogeology 2 – 2/1994:26-32

Wrigth EP, Burgess WG (1992) The Hydrogeology of Crystalline Basement Aquifers in Africa. The Geological Society London, 264 pp

Stober I (1995) Wasserführung des kristallinen Grundgebirges. Enke, Stuttgart, 191 pp

Table 1. Most typical data of the wells of the municipal area of Petrolina. The shallow wells have in general a good yield and better water quality. Deep wells with some exceptions have a low yield and lean to bad water quality

Sample	Depth [m]	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^-	pH	Q [l/h]	TDS	W-Type
486	22	90	6	27	10	129	7	4	214	6,7	100	532	Na-Fe-Cl-HCO3
442	26	190	9	453	171	1215	195	68	399	6,8	1000	2710	Ca-Mg-Cl
73	30	145	12	159	101	607	46	44	206	6,9	4800	1326	Mg-Ca-Na-Cl
372	33	14	10	38	11	11	15	14	163	6,9	3000	187	Ca-Mg-HCO3
106	58	146	7	78	35	156	103	17	326	7,3	6000	682	Na-Ca-Mg-HCO3-Cl
232	60	422	20	233	53	1320	112	29	131	6,7	2000	2328	Na-Ca-Cl
168	75	511	4	309	291	1735	333	217	392	7,1	300	3808	Mg-Na-Ca-Cl
283	93	758	18	174	127	1324	243	292	435	7,1	700	3383	Na-Cl
304	100	659	23,5	558	717	2245	2152	245	363	6,8	500	7036	Mg-Na-Ca-Cl-SO4

Determination of hydraulic properties in fractured aquifers in Austria

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A b s t r a c t : Deep groundwater formations often include aquifers within fractured, fractured-porous and, in carbonate rocks, karstified formations. Since practically all deep aquifers are effectively confined, not only the exact description of the groundwater flow but also the pressure diffusion, which is responsible for interference of neighbouring wells, are of great significance.
At selected deep wells in Austria pumping tests were evaluated and the hydraulic properties like transmissivity and storativity as well as the hydraulic diffusivity were determined. In addition to the pumping test evaluations, lab investigations on core samples were also carried out to find out the porosity and compressibility of some aquifers. On the basis of porosity and compressibility, storativity values were determined and compared with those from pumping tests. The number of wells in different geological areas as well as in different rock types (crystalline, carbonate, volcanic) permits a regional evaluation and classification of the aquifers.

INTRODUCTION

Aquifers possess two significant properties. They can store the liquid contained in their voids and transmit that liquid in the presence of appropriate gradients. These properties are characterised by the hydraulic parameters storativity and transmissivity. These two properties are responsible for the distribution of pressure in the aquifer. There are numerous methods available for evaluating the hydraulic properties of an aquifer. The most commonly used aquifer tests are pumping tests. The storativity can however also be calculated from the aquifer compressibility by virtue of the latter's elastic properties.

In the following, results are presented from evaluations of the hydraulic properties of fractured aquifers in Austria.

EVALUATION OF PUMPING TESTS

In order to be able to define both hydraulic properties, transient evaluation of pumping test data is required. However, the evaluation is rendered more difficult because, where small pumping tests are carried out on deep aquifers, well-bore storage and skin effect can influence the results. It is therefore important to evaluate and analyse the pumping test data not only numerically but also by plotting. The analysis of plots of the lines of water level decline and recovery permit influencing factors and circumstances to be identified and appropriately taken into account or eliminated.

If the aquifer fractures are fine and evenly distributed (homogeneous and anisotropic) and the flow is laminar, the methods developed for porous aquifers can be applied. However, in the case of specific fracture parameters, special methods can be called upon. In the bore holes investigated, these fracture parameters could only be defined to a limited extent, with the result that in most cases the simplest aquifer models had to be used. The evaluations presented were carried out using Aqtesolv software and application of the procedure of Theis, Cooper and Jacob, Papadopulos and Cooper (Şen 1995). The pumping test data were analysed in linear-logarithmic and log-log plots.

STORATIVITY AND AQUIFER COMPRESSIBILITY

The storativity S of a confined aquifer can be derived from the equilibrium of forces due to pressure and the deformation of the aquifer, being thus dependent on the elasticity and lending itself to description as follows (De Marsily 1986):

$$S = H \times g \times \rho \times (\alpha + n \times \beta) \qquad (1)$$

where H thickness (m), g gravitational acceleration (m/s^2), ρ water density (kg/m^3), α rock compressibility (Pa^{-1}), β water compressibility (Pa^{-1}), n porosity.

Using equation (1), the thickness was evaluated through the combined use of borehole measurements. The porosity was also derived either also from borehole measurements or laboratory experiments on core samples. The water compressibility is defined as a function of temperature and pressure, both of which are available from borehole measurements. The rock compressibility could only be derived from compression tests in a few cases and, in the event that no measurements were available, estimation was done using values from the literature (Lama, Vutukuri 1978, Stober 1986).

HYDRAULIC DIFFUSIVITY

The ratio of transmissivity to storativity, the hydraulic diffusivity a (equation 2), governs the propagation of changes in hydraulic head and the pressure diffusion in the aquifer (Singhal, Gupta 1999).

$$a = \frac{T}{S} = \frac{k}{S_S} = \frac{K}{\mu \times \beta_{tot}} \qquad (2)$$

where S_S specific storage (m^{-1}), k hydraulic conductivity (m/s), K permeability (m^2), β_{tot} total aquifer compressibility (Pa^{-1}), μ absolute viscosity (kg/m·s).

From equation (2) it is evident that the hydraulic diffusivity and so the propagation of changes in hydraulic head depend on the permeability, overall compressibility of the aquifer and absolute viscosity of the water. For pressurised aquifers having similar histories of geological formation, structures and compositions, the hydraulic diffusivity should be approximately constant and thus constitute a general characteristic hydraulic parameter.

RESULTS OF PUMPING TEST EVALUATIONS AND LABORATORY TESTS

By way of an example, the evaluation of the Längenfeld Thermal 2 well is presented here. In the area of the aquifer (open hole between 811 and 1865 m TVD), eclogite, orthogneiss and amphibolite are to be found. Through the borehole measurements, the water-bearing strata were sampled over a total vertical range of 60 m. Pumping tests, one short (18 days) and one long (67 days) were evaluated.

Analysis of recovery test after the short pumping test allowed the well-bore storage of the well to be identified and the

transmissivity to be calculated at $T = 1.3 \times 10^{-5}$ m^2/s. This was taken into account during evaluation of the long pumping test using the method of Papadopulos and Cooper, yielding the transmissivity $T = 1.0 \times 10^{-5}$ m^2/s and the storage coefficient $S = 3.2 \times 10^{-5}$ m^2/s. The latter value agrees well with that calculated from the aquifer compressibility.

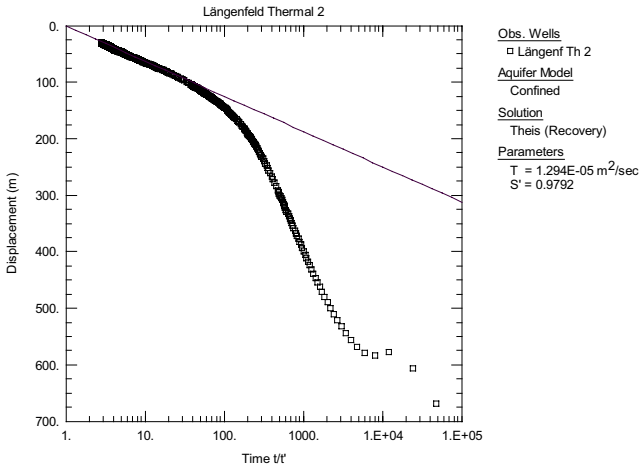

Figure 1. Evaluation of the recovery test after the short pumping test (Theis´ method)

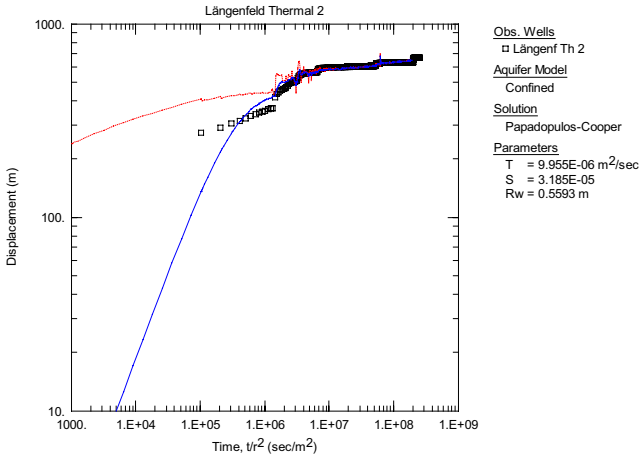

Figure 2. Evaluation of the long term pumping test considering well-bore storage (Papadopulos and Cooper´s method)

Because no core samples were available from the borehole, the storativity was calculated by estimating the rock compressibility according to equation (1) using the values H = 60 m, n = 0.047, T = 45 °C, p = 86.6 bar, $\rho = 990.3$ kg/m^3, $\beta = 4.3 \times 10^{-10}$ m^2/N, $\alpha = 3.35 \times 10^{-11}$ m^2/N (gneiss, after Stober 1986). This yielded a storativity of $S = 3.13 \times 10^{-5}$.

Detailed investigations (pumping tests, borehole measurements, laboratory tests on core samples) were carried out on the Römerquelle wells RQ 13E and RQ14E. Within the aquifer area of these boreholes were found compact, karstified and fractured dolomites and conglomerates. The porosities were evaluated by means of borehole measurements (neutron porosity, dolomite porosity) and core tests in the laboratory. Uniaxial pressure tests were also carried out. The results of the investigations and the hydraulic parameters calculated from them are summarised in Tab.1.

There was very good agreement between the storativites calculated from pumping tests and from compressibility in the case of Römerquelle 13E.

Table 1. Laboratory results from the RQ 13E and RQ 14E wells

Borehole/Test	RQ 13E	RQ 14E
Young's modulus (Pa)	3.26×10^{10}	5.40×10^{10}
Poisson's ratio (-)	0.21	0.12
α (Pa^{-1})	$3.06\text{-}5.33 \times 10^{11}$	$1.85\text{-}4.22 \times 10^{11}$
β (Pa^{-1})	4.75×10^{10}	4.75×10^{10}
H (m)	16.2	7.2
n (-)	0.14	0.11
ρ (kg·m^{-3})	999.7	999.6
T_W (°C)	11.5	11.1
S (-) from β_{tot}	$1.54 - 1.90 \times 10^{-5}$	$4.99 - 5.63 \times 10^{-6}$
S (-) from pump. test	$1.47 - 16.6 \times 10^{-5}$	$1.43 - 41.1 \times 10^{-5}$

SUMMARY

The transmissivities of the fractured aquifers investigated lie generally between 10^{-7} and 10^{-2} m^2/s. The highest transmissivities are to be found among the carbonate malm aquifers in the Molasse basin of Lower Bavaria-Upper Austria, whilst the lowest occur among the crystalline aquifers in the quarzites of the eastern foothills of the central Alps.

The calculated mean values of transmissivity cover a range of only ±150 %, where the varying effects of areas close to or distant from the sensor should be distinguished and any skin effect taken into account, whereas the storativities calculated by various methods often cover a range of two orders of magnitude for most boreholes.

Comparison of the hydraulic diffusivities of the aquifers studied allows the following observations to be made.

According to the local geological typology, a plausible range of hydraulic diffusivity can be declared for the carbonate aquifers in the Styrian basin (Graz Palaeozoic) in the range 0.5 to 8 m^2/s. The Malm aquifers of the Molasse basin generally exhibit a significantly higher hydraulic diffusivity between 6 and 1100 m^2/s, attributable to high transmissivity associated with the high degree of karstification. The hydraulic diffusivity of the karstified dolomite aquifers of the Römerquelle boreholes lies between 2 and 38 m^2/s, thus being between that of the carbonate aquifers of the Graz Palaeozoic and the Malm aquifers of the Molasse basin. The non-fracturing tertiary sandstone aquifers have hydraulic diffusivities approximately the same as those of the Palaeozoic carbonate aquifers in the same area (0.1-5.7 m^2/s). The crystalline aquifers investigated have relatively high hydraulic diffusivities in the range 0.15 to 3.4 m^2/s.

REFERENCES

Şen Z (1995) Applied Hydrogeology for Scientists and Engineers, Lewis Publishers, Boca Raton, 444 pp

Singhal BBS, Gupta RP (1999) Applied Hydrogeology of Fractured Rocks, Kluwer Academic Publishers, Dordrecht Boston London, 400 pp

Stober I (1986) Strömungsverhalten in Festgesteinsaquiferen mit Hilfe von Pump- und Injektionsversuchen. Geol Jb Reihe C, Heft 42, Hannover

De Marsily G (1986) Quantitative hydrogeology. Academic Press, San Diego, 440 pp

Lama RD, Vutukuri VS (1978) Handbook on Mechanical Properties of Rocks. Series on Rock and Soil Mechanics. Vol. I-II, 1st Printing, Trans Tech Publications, Clausthal

Groundwater modelling and bore selection in fractured rock environment

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A b s t r a c t : Majority of aquifers in the Northern Territory (N. T.) of Australia are in the fractured rocks. Therefore, the selection of bore sites is of the utmost importance. Fractures/faults alone can't guarantee water supply as highly fractured and weathered rocks may contain clayey materials blocking the bore. The Groundwater modelling is essential to know the behaviour of the aquifers for a long range prediction. A case history from the Adelaide River Township is sited here. Due to thick black soil cover, it was difficult to locate fractures in the field. However, air photos, satellite imageries and geophysical surveys were very useful. A shear zone was discovered and production bores were drilled on selected sites. It is a rule of thumb that the sustainable yield from fractured (non-carbonate) rock aquifers is usually about 20 to 30 % of the airlifted yield. Therefore test pump is essential to set the pumping rate.

INTRODUCTION

Majority of the aquifers in the Northern Territory (N. T.) of Australia are in the *Proterozoic* age fractured rocks and mostly are non-carbonate. Therefore, its importance is very high and one such case is the *Adelaide River Township* situated beside the *Adelaide River* and thus its name. It is about 110 km south of *Darwin*, the capital of the N. T. The Adelaide River Township became a major army encampment centre and hospital zone during the *Second World War*. Location is shown in the Fig.1. Its population is about 220.

Climate is tropical with two distinct seasons – *Dry* (cooler period) & *Wet* (rainy period) and the temperature ranges from 10^0 to 30^0 C. It rains only in the Wet Season between October and May with an average of 1650 mm per annum of which about 30% recharges the aquifers. The pan evaporation is about 2800 mm per year i.e. 7.7 mm per day.

Few bores were drilled by the Army during the *Second World War* and later by the *Water Resources Division* of the N. T. Government for local use. Very high contents of Mn and Fe in the groundwater have restricted the use of water. The groundwater investigations were carried out during Prowse (1983) and Verma (1991) to locate the potable water. During the 1991 investigation a *Shear Zone* was discovered in which there a reasonable water supply was found.

The fieldwork was essential to confirm the interpretations from air photos and satellite imageries. The geophysical traverses like the Transient Electromagnetic Method (*TEM*) and *Mis-a-la-masse* Electrical Resistivity were carried out successfully, which were very appropriate; refer Verma (1991) for the details. Bores were sited with caution to assure that they were not in the main faults/fractures because it has been seen from the past experiences that the yield in the highly fractured and weathered rocks are very low to nil due to usual presence of clayey materials in such conditions.

Bore construction is another major problem in these conditions as during the cementing the layers above the aquifers are so much fractured that the cement would leak into the aquifer region below and would cement the aquifers. This problem was solved by the drilling supervisor (Kundie 1991).

HYDROGEOLOGY

The area lies within the *Pine Creek Geosyncline* in which the sediments have gone under intense folding, faulting, uplifting, subsidence and regional (*greenschist facies*) metamorphism during 1800 Ma. Therefore, the most of the *Proterozoic* rocks in this area are fractured, which are reasonably good aquifers.

The Shear Zone (Fig.2) is about 2.5 km long, 300 m wide and 50 m deep bgl (below the ground level). The *Burrell Creek Formation* of the *Lower Proterozoic* age usually doesn't have good aquifers unless it is fractured as in this case.

The sustainable yield in the shear zone averages up to 3.0 L/s. But, the pumping rate was recommended to be 1.0 L/s due to high contents of Mn & Fe.

During the 1991 investigation, care was taken in siting of bores to avoid major faults and/or fractures in which rocks are found generally weathered and clayey. It also helped keeping the Mn and Fe contents low because the clay absorbs them easily. This action slightly helped in reducing both problems.

HYDROLOGY

General groundwater flow in the region is to the east during the Dry Season and primarily controlled by the elevation topography. In the Wet Season the groundwater flow is towards the river (west), however due to high water levels in the middle part, the flow is to the east also on the extreme eastern region.

The modelling in the shear zone was difficult but after trying different methods, the I*mage Well Theory* using the *Whip* Modelling program was found to be the best fit for the boundary condition. A total water supply of 930 kL/day (10.9 L/s) was required for the projected population of 220 in 1994. It meant that 250 kL/day (3.0 L/s) was needed to augment the existing supply. A series of bores were drilled including observation bores. *Airlifted yields* were up to 12.0 L/s. However, it should be noted that as a rule of thumb, the *sustainable yield* from fractured rock aquifers is usually found to be about 20 to 30% of the airlifted yield. The *test pumps* indicated that the sustainable yield of each bore is up to 3.0 L/s.

Three (3) production bores were drilled and constructed. The pumping rate was recommended to be 1.0 L/s for each bore to achieve the water supply demand.

Whip modelling program was used to compare to the *Theiss* curve and then used the *Jacob – Cooper* semi-log analysis to determine values of T & S. Transmissivity in the fractures was found to be different in the *strike* (up to 80 m^2/d) to the *across-strike* direction (up to 10 m^2/d). By reducing the surge or turbulence during the pumping would reduce the amount of Mn and Fe in pumped water.

WATER QUALITY

High contents of Mn and Fe in the groundwater are derived from the in-situ rocks (graphitic shales, siltstones, etc.). Clothes in the washing get blackish. Drinking water in the tap also gets black. The Mn and Fe look awful for the cooking purpose though they are aesthetic.

Few options were given to reduce the Mn and Fe contents are:

a) Blend the water from different bores,
b) Use Greensand Filtration,
c) Continuous regeneration in which Fe is reduced,
d) Intermittent regeneration,
e) Full treatment, but it is a high cost operation,

f) Start pumping with less surge and turbulence and

g) Have two separate water mains – the one with lower Mn & Fe contents for domestic use (drinking, cooking and washing clothes) and the another one with high contents
of Mn & Fe for all other uses.

ACKNOWLEDGEMENTS

Thanks to geophysicists Peter Rowston and Keith Martin for their ingenuity in geophysical survey to map the shear zone. Thanks to Drilling Supervisor Brian Kundie for solving the bore cementing problem on the spot.

REFERENCES

Furness CP (1982) Hydrogeophysical Report of Adelaide River, Report No. 28/13, Power And Water Authority, Darwin, N. T., Australia

Kundie B (1991) Drilling supervisor of the Adelaide River Township Groundwater Supply Augmentation Investigation, Report No. 30/1991, Water Resources Division, Power And Water Authority, Darwin, N. T.,Australia

Prowse G (1982) Adelaide River Water Supply Investigation of Groundwater Resources, Report No. 30/1983, Water Resources Division, Dept. of Mines &Energy, Darwin, N. T., Australia

Verma MN, Martin K, Pidsley D (1991) Adelaide River Township Groundwater Supply Augmentation Investigations, Report No. 30/1991, Water Resources Division, Power And Water Authority, Darwin, N. T.,Australia

Well Hydraulics Interpretation Program (WHIP) Version 3.22,Hydro Geo Chem. Inc. G/W Consultants, Tucson, U. S.A., July 1988

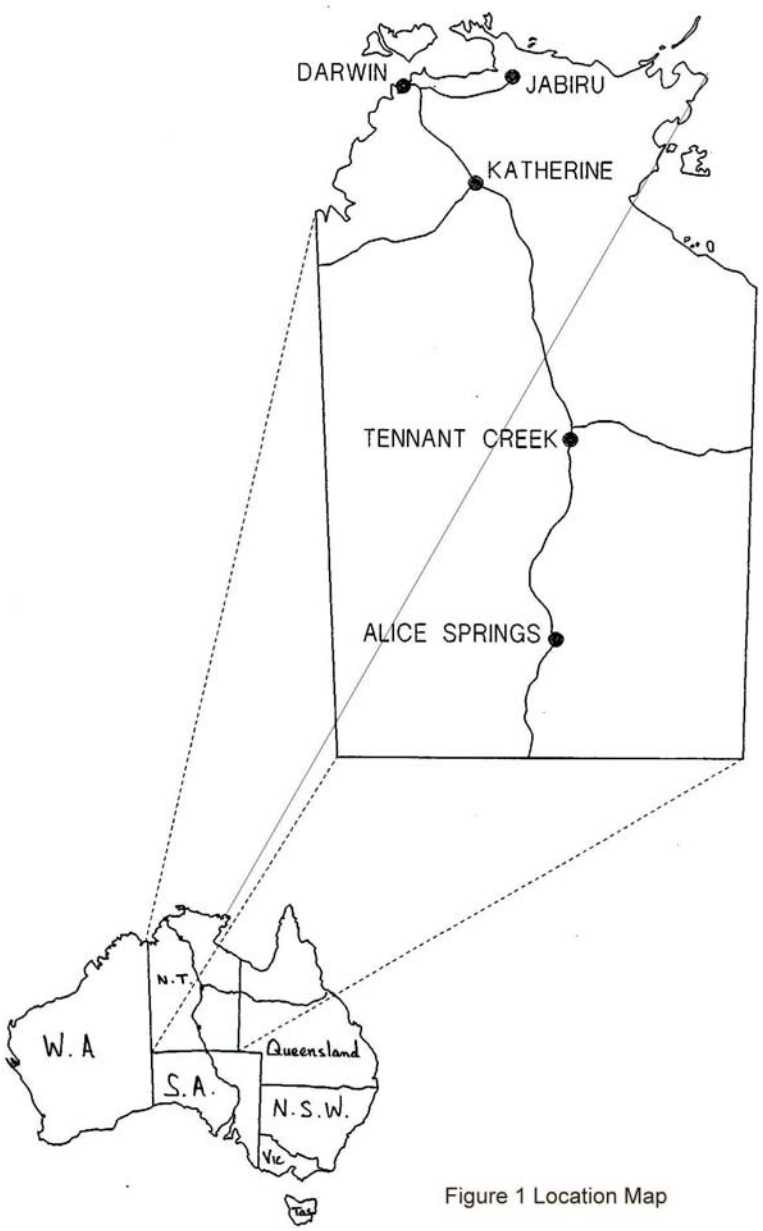

Figure 1 Location Map

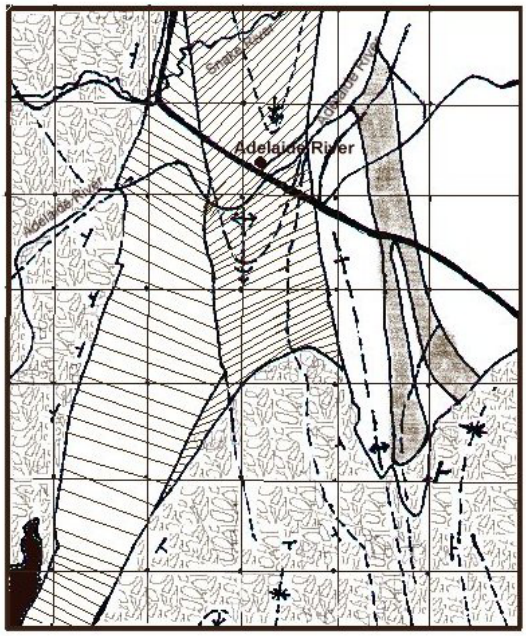

Figure 2 Geology Map

Determining a representative hydraulic conductivity of the Carnmenellis Granite of Cornwall, UK, based on a range of sources of information

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A b s t r a c t : The Carnmenellis granite outcrop in SW England has been the subject of a number of hydrogeological investigations over many years. This paper sets out to review the data available on the range, distribution and variation of hydraulic conductivity of the granite based on information drawn from a number of studies and sources. The upper 30 m to 100 m of the granite are highly to moderately weathered and support small scale water abstractions. Beneath this the unweathered granite is still fairly permeable to considerable depths.

GEOLOGY

The Carnmenellis granite forms a plateau, 150 to 250 m above sea level. The outcrop is almost circular in plan, 10 to 12 km diameter and covering an area of 75 km^2. It is located in the south west peninsular of Cornwall and its boundaries are within 1 km of the south coast, 6 km of the north coast and about 25 km from Land's End to the west, which marks the south-westernmost extremity of mainland Britain.

The Carnmenellis granite is one of a series of outcrops of the Cornubian Batholith that underlies Cornwall and much of Devon in South West England, extending some 250 km from Dartmoor in the east to the Isles of Scilly in the west. The granite is Late Carboniferous in age and has been dated at around 290 Ma (Chen *et al.* 1993). A high degree of mineralisation occurred during the Permian and this has formed the basis of the extensive copper and tin mining industries of the 18th and 19th centuries.

The granite is generally coarse grained, though medium to coarse grained toward the centre of the outcrop and with some fine grained intrusions. It is of feldspar-rich porphorytic muscovite-biotite composition and in places has been altered by toumalinisation, griesenisation and kaolinisation (Edmunds *et al.* 1990).

Deep weathering of the granite, probably initiated in late Tertiary times, was influenced by NW-SE trending features (Osman 1928) and fissures are substantial to depths of 50 to 100 m.

During periglacial conditions in the Pleistocene the top of the granite was exposed to extreme weathering and Head deposits make up the top few metres in some places. The Head consists of frost shattered angular granitic fragments in a sandy matrix.

The most common set of steeply dipping joints trend NNW and ENE, parallel to major faults and mineral lodes, respectively, and a subordinate pair trend WNW and NNE (Edmunds *et al.* 1990). In the uppermost 50 m, or so, horizontal joints are significant, though decreasing dilation with depth reduces their impact below this (Heath 1985).

HYDROLOGY AND HYDROGEOLOGY

Average annual rainfall varies from 1.2 m per year around the perimeter of the outcrop to 1.5 m per year at the centre. Four main rivers (the Red, Kennal, Kenwyn and Cober) drain the plateau, outward from the centre. The courses of each of these rivers follow major fault lines and lineaments in the granite. Three public supply reservoirs are located on the outcrop, impounded by dams. The rivers tend to show very high baseflow indices, of around 70%. This is probably due to the high permeability of the soils and upper weathered zones, promoting recharge, and possibly the hydrological impact of historic mining and mine drainage.

The Carnmenellis granite is classified as being a minor aquifer, locally important for some private supplies. The water table is rarely more than 10 m below the ground surface and is constrained by mine workings, springs and the levels of streams and rivers. Borehole yields rarely exceed 100 m^3/day and average around 50 m^3/day with a 95% probability of striking water bearing fractures within 20 m of the ground surface (Edmunds *et al*. 1990).

HYDROGEOLOGICAL INFORMATION

Information on the hydrogeological characteristics of the granite were obtained from a number of sources, including:

Mining

Flooded mine workings affect the hydrogeology of the granite by increasing the overall porosity and providing zones of preferential flow. Traditionally, mines have been dewatered using adits (near-horizontal drainage tunnels bored from the lowest nearby locations in river valleys to intersect mineral-rich lodes and drain the groundwater). Surface water power was also used to drive pumps to dewater mines from below adit level. From the mid-19th century, steam power replaced water power and enabled mines to be driven to much greater depths, the water being pumped up to adit level from where it discharges to watercourses.

Whilst water above adit level tends to provide a fairly diffuse fracture inflow, deeper seeps tend to be controlled by major fractures along discontinuities and major fault zones.

The last working deep mine in Cornwall was South Crofty, which penetrated deep into the Carnmenellis granite and closed in 1997, leading to a groundwater rebound that decanted at adit level (into the Red River) in 2000. Prior to closing, pumping rates from different levels in the mine were as follows: 350 m depth = 70-120 L/s; 600 m depth = 140-170 L/s; 680 m depth = 30-40 L/s; 750 m depth = 10 L/s. The ranges quoted above reflect seasonal variation, which reduces with depth. Whilst these inflows depend on the horizontal as well as the vertical extent of the mine workings, and cannot directly be related to permeability, they do show that significant inflows still occur at great depth and that lateral flow into the mine system occurs, as direct recharge is intercepted at the upper levels.

Geothermal energy research

A quarry close to the centre of the granite outcrop was the site of a deep drilling project to investigate the potential of hot dry rock (HDR) geothermal energy. Two boreholes were drilled into the granite to depths of 2500 m.

Hydraulic testing of the deep boreholes showed an *in situ* hydraulic conductivity of around 1.5×10^{-10} m/s at 2000 m depth (CSM 1984) though this was increased by deliberate hydrofracturing to 1×10^{-8} to 5×10^{-8} m/s between 2300 m and 2400 m depth (Parker 1989).

Deep packer tests

A series of deep boreholes were drilled up to 700 m depth at a quarry in the north west of the granite as part of a tracer test for research into fractured flow implications for underground nuclear repositories (Heath and Durrance 1985).

Six boreholes were drilled in the quarry within a floor area of just 20 m by 20 m. Four of these were packer tested using 1 m sections; three were tested to about 200 m depth whilst the fourth was tested to 650 m depth. The results are shown in fig.1. They generally show hydraulic conductivities in the range 10^{-9} to 10^{-5} m/s, with 10^{-8} to 10^{-7} m/s being more typical. It is worth noting that some of the highest flows were encountered at the deepest levels.

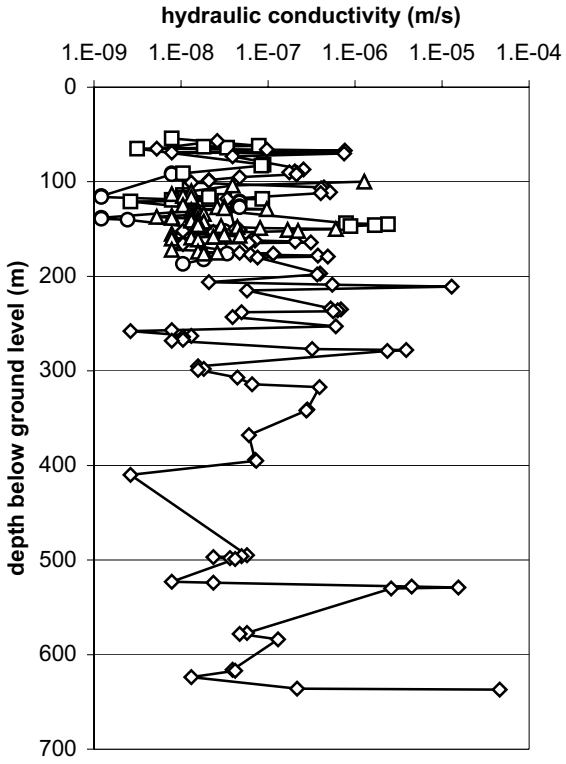

Figure 1. Deep packer tests, data from Heath and Durrance (1985)

Numerical modelling

Recently, hydrogeological investigations have taken place in relation to the proposed conversion of a quarry in the south west of the granite to a landfill site. In connection with the hydrogeological assessment of the site a numerical model of groundwater flow in the region around the quarry was constructed and calibrated against piezometer monitoring data (unpublished, by the author). The model simulated the near surface movements of groundwater within the catchment area around the quarry, between boundaries generally provided by river systems and in steady state only.

An areal rainfall recharge rate of 0.365 m/year was used (this value of 1mm/day is generally accepted as a reasonable groundwater recharge rate for Southern England, as an approximate guide). By trial and error, a satisfactory fit with field data was obtained using a two-layer model with a 50 m thick upper layer (i.e. extending 50 m below the surface topography) having a hydraulic conductivity of 10^{-5} m/s and a 350 m thick lower layer with a hydraulic conductivity of 10^{-7} m/s.

CONCLUSIONS

The hydraulic conductivity of the granite aquifer may be described in terms of four depth-dependent zones depending on the degree of weathering:

1. Extremely weathered uppermost zone

Flow here is intergranular due to the high degree of weathering of the granite. This zone may be virtually absent or 2 to 3 m in depth. Its high permeability promotes groundwater recharge but has little other effect on the regional hydrogeology as it is generally above the water table.

2. Highly weathered upper zone

Flow here is secondary through fractures but can generally be described as diffuse. This zone extends from surface (or the base of zone 1) to between 30 and 100 m depth. The hydraulic conductivity is generally between 10^{-4} and 10^{-6} m/s. This is the dominant zone for shallow groundwater flow and for water abstractions from wells.

3. Partially weathered middle zone

This zone extends from the base of Zone 2 to around a few hundred metres depth. The hydraulic conductivity is generally around 10^{-7} to 10^{-8} m/s though regions of both higher and lower permeability exist within it. Horizontal fractures are generally absent due to overburden pressures.

4. Unweathered lower zone

This zone extends from the base of zone 3. For most intents and purposes, this zone may be considered impermeable; the hydraulic conductivity is around 10^{-10} m/s or less. However, drilling or driving shafts into this zone may provide stress relief that allows fractures to dilate, increasing the permeability of deep joints and fault zones.

REFERENCES

Chen Y, Clark AH, Farrar E, Wastneys HAHP, Hodgson MJ, Bromley AV (1993) Diachronous and independent histories of plutonism and mineralization in the Cornubian Batholith, southwest England. Journal of the Geological Society 150:1183-1191

CSM (1984) CSM geothermal energy project. Low flow rate hydraulic tests Phase 2 report no. 2-52. Camborne School of Mines, UK, 110 pp

Edmunds WM, Davenport MF, Smedley PL, Kay RLF, Robins NS, Collier C, Burfitt KA (1990) The Carnmenellis Granite – hydrogeological, hydrogeochemical and geothermal characteristics. British Geological Survey, Map

Heath MJ (1985) Geological control of fracture permeability in the Carnmenellis granite, Cornwall: implications for radionuclide migration. Mineralogical Magazine 49:233-244

Heath MJ and Durrance EM (1985) Radionuclide migration in fractured rock: Hydrological investigations at an experimental site in the Carnmenellis granite, Cornwall. Commission of the European Communities: Nuclear science and technology, EUR 9668EN

Osman CW (1928) The granites of the Scilly Isles and their relation to the Dartmoor Granite. Quarterly Journal of the Geological Society of London 84:258-290

Parker RH (1989) Hot dry rock geothermal energy, Phase 2B final report of the CSM Project, Vol 1. Permagon Press, pp 677

Hydrogeological significance of fractures within the Augustus river catchment

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A b s t r a c t : Drilling data have highlighted the presence of both porous media aquifers within the weathered profile (shallow and Zersatz aquifers) and fractured rock aquifers within the basement rocks and in the overlying weathered profile. A combination of barometric efficiency measurements and detailed groundwater level measurements indicate these aquifers are well connected. This connection is thought to be due to the presence of geological structures that have been identified within the basement rocks extending through the weathered profile. The effects of these fractures on hydrogeological responses are presented. The numerical representation of these fractures using the equivalent porous medium (EPM) and discretely fractured porous medium (DFPM) techniques was then investigated. The outcome of these investigations have shown that subtle improvements may be possible by using the DFPM technique for numerically simulating groundwater flow within fractured porous media environments such as those found within the Augustus River catchment.

INTRODUCTION

The study area is the Augustus River catchment located about 300 km south of Perth (capital city) and about 42 km east of Bunbury (nearest major city) in Western Australia (Fig.1). The lease boundary of an alumina refinery operated by Worsley Alumina Pty Ltd (Worsley) encompasses the study area.

A combination of characterisation and modelling has highlighted that fractures are a significantly component of the hydrogeology of the Augustus River catchment.

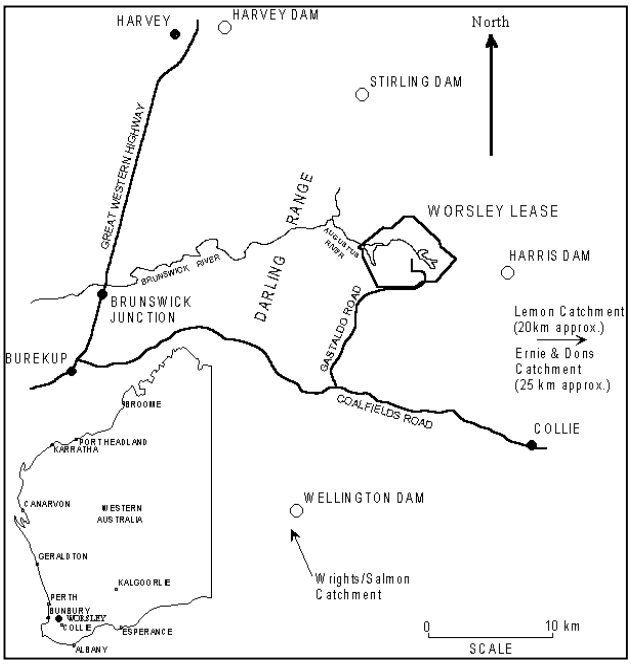

Figure 1. Locality Plan

HYDROGEOLOGY

Wilkes *et al.* (2002) have identified a number of aquifers in the study area. These include:

- shallow weathered zone aquifer (shallow aquifer)
- deep weathered zone aquifer (locally referred to as the Zersatz aquifer)
- fracturing within the bedrock (fractured bedrock aquifer).

The conceptual hydrogeological regime of the study area has been presented by Wilkes *et al*. (2002) and is reproduced in Fig.2. Of importance is the fracturing of the basement rocks, which is associated with quartz veins more commonly along the margins of intruded dolerite dykes. The fractured quartz veins are also known to extend throughout the overlying weathered profile (Fig.2).

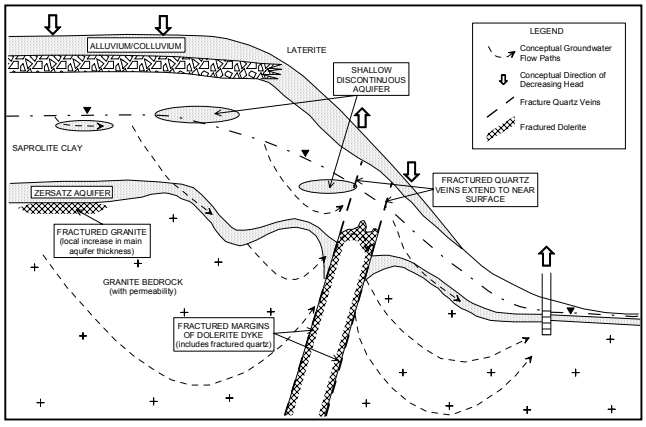

Figure 2. Conceptual Hydrogeology

HYDROGEOLOGICAL SIGNIFICANCE OF FRACTURES

The identified fractured quartz veins conceptualised in Fig.2 have been found to be an important component of the hydrogeology. The fractures:

- modify the distribution of heads along a flow line
- link the 3 main aquifer systems, such that the entire system reacts as an unconfined aquifer
- promote rapid episodic recharge to the aquifers.

The change in the distribution of heads within the study area as a result of the fractures is conceptualised in Fig.2, which has largely been devised by review of over 20 years of groundwater monitoring data. The figure shows that the direction of decreasing head with depth reverses from downward heads in the upper parts of the catchment to upwards heads on the up-gradient side of the fractured margins of the dolerite dykes, then reverts to downward head on the down-gradient side of the dykes. Fracturing at the base of weathering of the dyke prevents groundwater 'damming up' behind the dyke because the fractures increase the transmissivity and allow groundwater to readily flow from one side of the dyke to the other.

Groundwater level measurements were collected (measured every 30 minutes) for about 1 year from a number of bores individually screening each of the three aquifers. An example of this data is shown in Fig.3. The response of each of the aquifers to various rainfall events is almost identical despite the shallow and Zersatz aquifers being separated by more than 15 m of relatively low hydraulic conductivity saprolite clay. This type of response could only be observed within a very well connected unconfined aquifer system.

During the summer periods, subtle yet measurable fluctuations of the groundwater level were observing occurring as a result of barometric pressure changes. Calculations revealed very low barometric efficiencies for the Zersatz and fractured rock aquifers, which is indicative of unconfined aquifer systems. Fractured quartz veins are interpreted to be the direct result of the measured responses and the entire sequence responding as an unconfined aquifer.

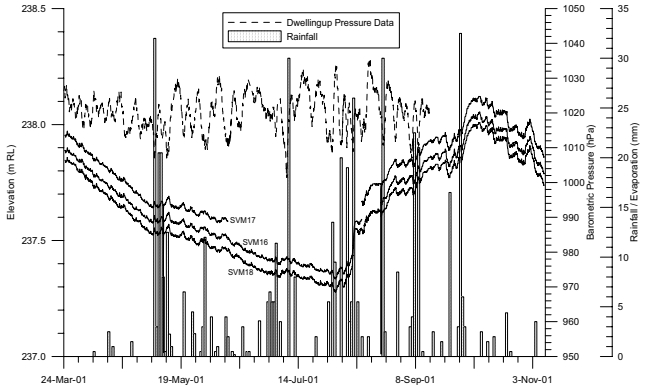

Figure 3. Detailed Groundwater Level Measurements

Fig.4 shows the rapid response of the aquifer system to the first winter rainfalls (measured every 5 minutes). The groundwater levels rise almost immediately following the beginning of the rainfall event, with the peak in groundwater level occurring about 0.5 days after the rain event. The timing of the peak represents a velocity of about 18 m/day, which is extremely high for an unsaturated clay rich profile. Fractures extending throughout the weathered profile to the near surface region are inferred to be the cause of these measured responses.

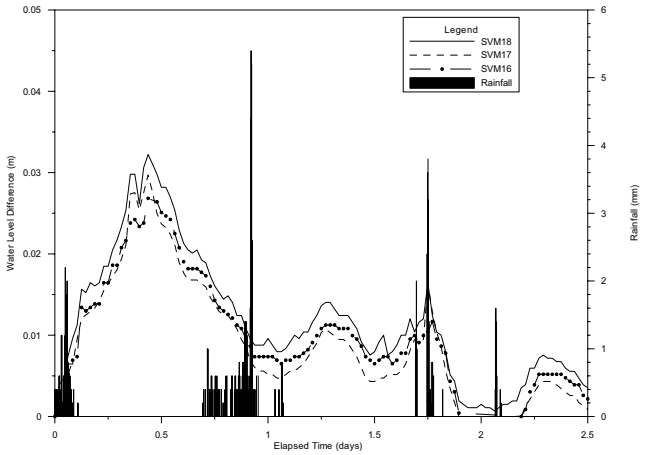

Figure 4. Rapid Recharge Responses

It is clear from the above evidence that the fractures are an important component of the hydrogeology within the Augustus River catchment.

NUMERICAL SIMULATIONS

An assessment of the relative performance of the equivalent porous media (EPM) and discretely fractured porous media (DFPM) modelling techniques has been undertaken within the study area. Both models were constructed using FeFlow (Diersch 1998). The numerical simulations were compared with measured field data.

The area chosen for simulations contained a dolerite dyke with fractured margins that crosscut an excavated trench that is in direct hydraulic connection with the shallow aquifer. The head within the trench was elevated for a transient period following an intense winter rainfall event. The measured transient responses within the trench and down-gradient monitoring bores screening each of the aquifers were used to calibrate each of the EPM and DFPM models. An example of the measured response within a bore screening the fracture and the calibrate simulation using the EPM and DFPM models is shown in Fig.5.

A comparison of the calibrated numerical simulations has found:

- an almost identical calibration to steady state groundwater levels could be achieved using the EPM and DFPM models
- the DFPM model simulated the draining portion of the transient simulation a little more accurately than the EPM model
- the DFPM model simulated the timing of the groundwater peak a little more accurately than the EPM model
- the DFPM model was relatively insensitive to changes in the storage parameter assigned to the fracture, while the EPM model was very sensitive to the assigned storage parameter.

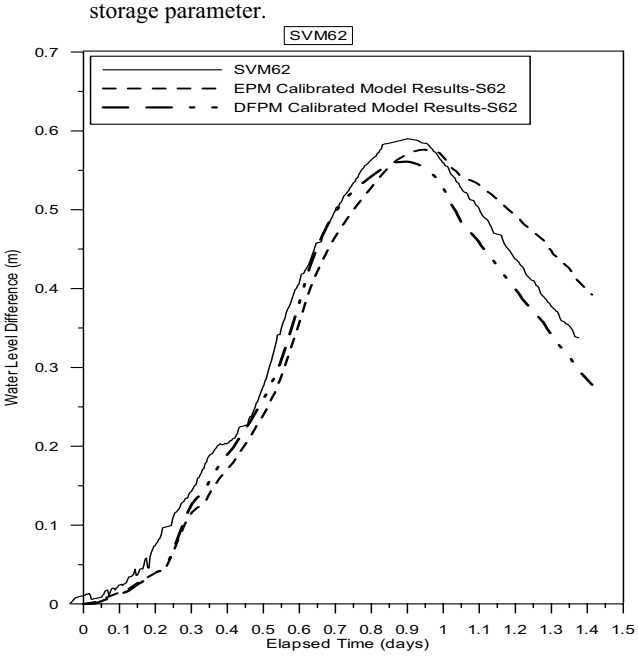

Figure 5. Comparison of Measured Groundwater Levels and Simulated Levels using both the EPM and DFPM Models

REFERENCES

Diersch HG (1998) FeFlow Reference Manual. WASY Institute, Berlin

Wilkes SM, Clement TP, Otto CJ (2002) The hydrogeology of the Augustus River catchment, submitted to Hydrogeology Journal

Estimating the change of fracture volume with depth at the Koralm Massive, Austria

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A b s t r a c t : The fracture network and its fracture sets predominantly determine the permeability and storage capacity of fractured aquifers. The hydrogeological effectiveness of fracture sets can be statistically characterised by analysing the geological spatial attributes (trend, plunge, frequency) and the hydraulic relevant attributes (aperture, length, linear degree of separation, termination) of fractures. Fracture attributes are recorded at a surface-exposure and along a drilling in the area of Koralm, Austria, both belonging to the same geological and tectonic unit. It could be shown with discrete fracture modelling that for this geological unit the fracture set volumes correlate with depth by an exponential function.

INTRODUCTION

For numerical modelling of fractured aquifers it is necessary to determine and quantify the hydraulic attributes and the spatial distribution of the fracture network. At surface-exposures the fracture network can be recorded with the scanline method and subsequently statistically analysed. As a result the hydrogeological effectiveness of the individual fracture sets can be estimated.

Surface-exposures and their fracture network are predominantly influenced by weathering and slope tectonics. Boreholes can give an important complementary information for the interpolation of the fracture network and its attributes into depth. In this work it is tried to combine fracture data observed at an exposure with fracture data obtained along a borehole to improve the estimation of a three-dimensional fracture network. With discrete fracture modelling it is tried to extrapolate the modification of the fracture set volumes into depth.

EXPOSURE ANALYSIS – METHODOLOGY

The characteristics of fracture sets can be estimated by the statistical analysis of fracture attributes like trend, plunge and the frequency of fractures and like averaged aperture, length, linear degree of separation and the termination of the fractures (ISRM 1978). The term fracture is defined as any significant mechanical break of negligible tensile strength in a rock (Priest 1993). This term makes no distinction concerning the age, geometry or mode of origin of the feature.

Sampling and pre-processing

In the area of Koralm, Austria the exposure KOR20 and the drilling TB02/00 were selected for analysing the modification of the fracture network into depth. Both belong to the same geological unit (Stainzer Plattengneis) with the same tectonic stress regime. The scan-line sampling technique was applied for the data recording. At KOR20 79 fractures and their attributes were recorded along 3 scanlines with a total length of 19,4 m.

In advance to the statistical analysis some inherent biases have to be corrected by weightings and estimations. This includes biases caused by a) the sampling technique itself (Kulitulake *et al.* 1993, Bäumle *et al.* 1998) b) the immeasurable attributes (aperture, length) of fractures located at the exposure face and c) the varying orientation of scan lines to the orientation of the fractures. Therefore, the maximum trace length was standardized with 2 metres and the maximum averaged aperture with 1 centimetre deduced by existing data. The fractures were standardized by their angle between the fracture and the scan line. The immeasurable fractures attributes on the exposure face were statistically estimated using the attributes of similar orientated fractures (Harum *et al*. 2001).

Clustering – estimation of fracture set volume

Cluster analysis attach objects, in this case fractures, to groups depending on their distance. Fractures within one group have a low "distance" and their attributes should be similar. The distance between two groups should be as large as possible. Thus the structural-geological and hydraulic relevant data of fractures are statistically combined (Harum *et al*. 2001). The two different groups of attributes should be integrated in the distance calculations. So for the calculations the "mixed distance" was taken and further on for the clustering either hierarchical or fuzzy c-mean clustering (Harum *et al*. 2001) was used.

Based on the results of the clustering it was possible to estimate the fracture set volumes assuming that the averaged aperture and the linear degree of separation continue into the rock mass as they are recorded on the surface. The clustering of KOR20 identified out three clusters. The biggest volume is calculate for the cluster 2 with about 0,32 % (Tab.1).

BOREHOLE ANALYSIS

Because of its linear character a borehole can be regarded as a scan line into depth. Borehole TB02/00 was explored with an acoustical borehole scanner and detailed core analysis. The combination of these investigating methods enhanced the data recording of the aperture and the spatial orientation of the fractures. In five different sections (Tab.1) the fracture attributes were recorded analogue to the data recording along the scan lines. It was assumed that the trace length distributions of the individual fracture sets along the borehole and on the surface-exposure are the same. So the fracture network along the borehole was statistically analysed with the same methods as the data of the surface-exposure. For each section the cluster distribution and the estimated fracture set volumes were calculated (Tab.1).

Table 1. Cluster volumes of the surface-exposure KOR20 and the 5 borehole sections of TB02/00 including the depths

section	depth (m)	cluster 1	cluster 2	cluster 3	total
		vol.%	vol.%	vol.%	volume
KOR20	0	0,05	0,32	0,2	0,57
Sec 01	311 - 359	0,01	0,06		0,07
Sec 02	434 - 446	0,01		0	0,01
Sec 03	503 - 537	0,01	0,02	0,01	0,04
Sec 04	572 - 614	0	0,02	0,01	0,03
Sec 05	619 - 649		0,02	0,01	0,03

In each section of the borehole the clusters have approximately the same spatial orientation as the clusters of the surface exposure. In all sections cluster 2 has the biggest fracture volume ranging between 0,06% and 0,02% and the other clusters are clearly smaller (about 0,01%).

MODELLING

The borehole and exposure analysis yields clusters for the depth below 300 metres and at the surface. To get also data between 300 metres and the surface a discrete fracture network is generated with the software Fracman (Dershowitz *et al*. 1998 and 1999) based on the data of TB02/00 and KOR20. The model region is dimensioned by a slab with 30 x 30 x 650 metres surrounding TB02/00. The fracture network model was calibrated iteratively starting with a polynomial function describing the reduction of the fracture set volumes correlated to depth by comparing the computed and the observed fracture attributes at the top of the slab and in depths below 300 metres. In addition to the existing data (Tab.1) further clusters and their volumes are calculated in the depths of 30, 60, 100 and 250 metres. The most satisfying fit could be obtained with an exponential function (Fig.1). The data of the borehole analysis and the additional calculated data enhance the continuing quantification of the volume reduction correlated to depth.

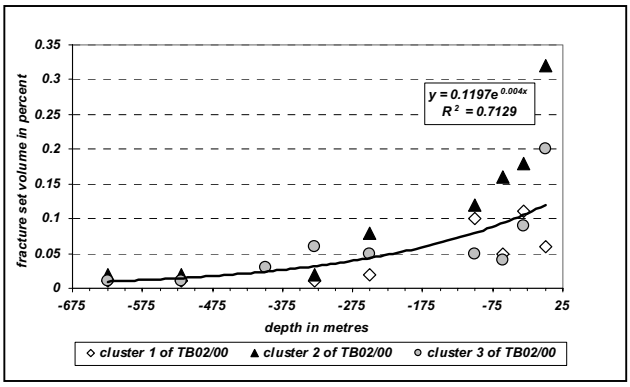

Figure 1. Correlation of the fracture set volumes to the depth

DISCUSSION

Fig.1 shows that the highest reduction of the cluster volumes can be observed for cluster 2 . Between the depth of 300 metres and the surface the variation of the individual cluster volumes comparing for each depth is much higher than below 300 meters. This is strongly influenced by the persistent higher volumes of cluster 2 (black triangles in Fig.1). Below the depth of 300 metres all the cluster volumes range between 0,01 and 0,02 %. So the cluster volumes have a different distribution below the depth of approximately 300 metres than above.

Weathering and slope tectonics influence surface-exposures causing the loosening of the fracture network. So the reduction of the fracture set volumes following the exponential function seems to be a consistent approach considering the geological environment.

For further investigations it is planned to measure the fracture attributes with optical borehole measuring techniques over the total length of the borehole. These logging results can be compared with the calculated cluster volumes of the discrete fracture model. Thus, the assumptions for the clustering and the estimation of the fracture set volumes will be investigated in more detail. Furthermore, the results of the fracture network characterisation will be related to results of hydraulic borehole tests to get an idea about the hydraulic attributes related to the fracture set volume.

SUMMARY AND CONCLUSION

Fracture networks have to be considered in the definition of hydrogeological units. So the first step of the presented approach was developed at exposures to characterize the individual fracture sets and to estimate their volumes. This approach combines the geological spatial fracture attributes with the hydraulic relevant attributes. Two different clustering methods, hierarchical and fuzzy c-mean, were applied to determine the fracture sets. The scan line sampling allows integrating borehole data in the calculation and interpretation into depth. The reduction of the fracture set volumes correlated to depth was modelled using a stochastic fracture network model and showed an exponential trend for the investigation area Koralm.

It could be shown that with this method it is possible to determine and to quantify the modification of the fracture network into depth. This approach is based on several assumptions that will be analysed in more detail in the future. Nevertheless this method can help in creating conditioned fracture networks including the spatial distribution of fracture attributes as an input for numerical modelling of flow in fractured aquifers.

REFERENCES

Bäumle CC, Hötzl H, Thüringer C, Witthüser K (1998) Untersuchungen zur Einrichtung eines Festgestein-Naturmeßfeldes. AGK 50, 29-50

Dershowitz W, Lee G, Eiben T, Ahlstrom E (1998) Meshmaster Discrete Fracture Mesh Generation Utility. User Documentation. Version 1.55. Golder Associates Inc., Seattle, 44 pp

Dershowitz W, Lee G, Geier J, Hitchcock S, LaPointe P, Cladouhs T (1999) FracWorks95 Discrete Feature Simulation. User documentation. Version 1.3 Golder Associates Inc., Seattle, 139 pp

Harum T, Hofrichter J, Kleb U, Kupfersberger H, Poltnig W, Reichl P, Reinsdorff S, Ruch C, Schön J, Strobl E, Winkler G (2001) Erfassung von Fließprozessen zur hydrogeologischen Bewertung von klüftigen Festgesteinen: unpublished report, Joanneum Research GmbH, Graz, 124 S

ISRM (1978).Suggested methods for the quantitative description of discontinuities in rock mass. Int J of Rock Mech a M Sc 15:319-368

Kulitulake PHW, Wathgala DN, Stephansson O (1993) Joint network modelling with a validation exercise in Stripa Mine Sweden. Int J of Rock Mech a M Sc 30:503-526

Priest SD (1993) Discontinuity analysis for rock engineering, 1st ed. Chapman & Hall, London, 473 pp

Experience of fractured aquifers in Ireland

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A b s t r a c t : Water supply in rural areas of Ireland generally depends on groundwater from fractured aquifers, which rarely behave like textbook examples. Studies of pumping test and water level monitoring data are helping us to characterise these aquifers.

- Pumping tests can give very different data sets under different water level conditions, e.g. up to tenfold increases in drawdown in nearby observation wells in dry as compared with wet periods.
- Short pumping tests may approach equilibrium, but longer tests often reveal a continued or accelerated water level decline.
- Step tests in unconfined fractured aquifers often show substantial falls in specific capacity as the pumping rate increases.
- Within a given aquifer, boreholes can display a wide range of yield-drawdown characteristics, but a sufficiently large data set can produce a representative 'profile'.
- Long-term water level decline may be induced by near-continuous pumping, due to low storage and hydraulic barriers.

INTRODUCTION

Water supply in rural areas of Ireland generally depends on groundwater from fractured aquifers, which rarely behave like textbook examples during pumping. Pumping test and water level monitoring data are helping in aquifer characterisation.

VARIATION IN PUMPING RESPONSE WITH WATER TABLE FLUCTUATION

Pumping tests can give very different data sets under different water level conditions. Four production wells in fractured and karstic limestone aquifers in County Cork, in the south of Ireland, have nearby observation wells (18 m away) equipped with automatic water level recorders. Every period of pumping (typically 10–16 hours per day) becomes, in effect, a pumping test. The records over several years indicate a twofold to tenfold increase in drawdown in the observation wells in dry weather conditions as compared with wet weather conditions (fig.1).

PUMPING TESTS

Pumping test interpretation requires identification of the location of the main water-bearing fractures in the pumping well. Significant changes often occur when the pumping water level falls below a major fracture (fig.2a).

Short pumping tests in unconfined fractured aquifers often fail to adequately represent the sustainable yield characteristics of a well. Pumping tests in new wells for public supply in Ireland are commonly of three days duration. Such tests may appear to approach equilibrium, but longer tests will often reveal a continued or accelerated decline in local water levels. Consequently, the relatively short tests routinely carried out (often without hydrogeological supervision) can be misleading.

One such example is from a fractured Carboniferous sandstone aquifer at Mallow Hospital (Kilknockan), in north Co. Cork. The driller estimated from a short air-lift test a well 'yield' of about 22 L/s. A four-day test initially appeared to confirm this, but towards the end the water level decline began to increase, indicating that the sustainable yield was much lower. A subsequent 11-day test (fig.2b) proved this to be true, and the sustainable yield is no more than about 9 L/s.

Other tests in fractured aquifers demonstrate this feature, though over shorter periods.

STEP TESTS IN UNCONFINED FRACTURED AQUIFERS

Step tests in unconfined fractured aquifers characteristically show rather steep falls in specific capacity as the pumping rate increases. Fig.3 presents data from several wells illustrating this feature.

Q/SC PROFILES

The characteristics of fractured aquifers (especially where unconfined), as deduced from pumping test data, must be viewed in a local context.

- Different characteristics can be estimated from pumping tests in the same well under different water table conditions (as in fig.1) and at different pumping rates (fig.3).
- Pumping tests in different boreholes in the same aquifer can give very different data, even where the wells are close together and of similar depth, diameter, construction, etc.

Hence it can be very difficult to characterise a given fractured aquifer in terms of its 'average' or even 'typical' properties, especially Transmissivity. It seems that aquifer properties can only be regarded as even approximately true for the immediate vicinity of the tested location. Across the aquifer as a whole, apparent transmissivity values can vary over several orders of magnitude. Where, as in Ireland, well-conducted pumping tests are all too rare, the problem is compounded.

To help characterise fractured aquifers with poor data sets, we are using the concept of 'well productivity' ratings (Wright 2000). We examine values of Specific Capacity (SC) in the context of the relevant discharge rate (Q), on a 'Q/SC Graph' (fig.4a). Each data point falls into one of 5 Productivity classes: I (high) to V (low). The Productivity values from boreholes in a given aquifer (given sufficient data points) then provide a 'Q/SC profile' for that aquifer. A major ('Regionally Important') aquifer should have a profile which is weighted towards the top end (fig.4b), whereas a poor aquifer's profile is heavily weighted towards the bottom end (fig.4c). We are still developing this method to help us discriminate between aquifers in a meaningful and defensible way.

LONG TERM WATER LEVEL DECLINE

Despite Ireland's humid climate, which ensures that potential groundwater recharge is abundant in most places, near-continuous pumping can induce long term water level decline, probably due largely to the generally low storativity of the aquifers and the frequency of hydraulic barriers such as faults. One example in Ireland is known from Templemore, County Tipperary (fig.5). The decline can be increased in areas where recharge is impeded by thick, poorly permeable superficial deposits, such as glacial tills with a high clay content.

REFERENCE

Wright GR (2000) QSC Graphs – An Aid to Classification of Data-Poor Aquifers in Ireland. In: Groundwater in the Celtic Regions, Geol Soc London Special Publications 182:169-177

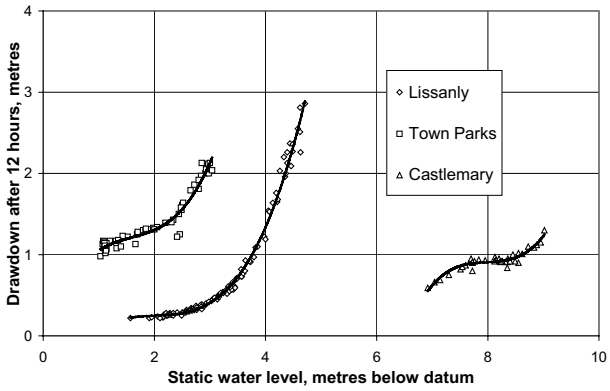

Figure 1. Variation of drawdown with static water level, Cloyne (Co. Cork) wellfield

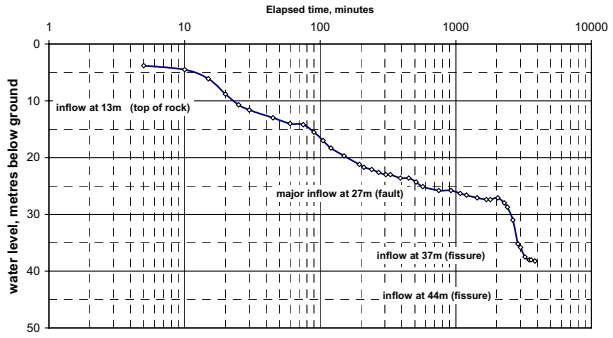
Elapsed time, minutes
water level, metres below ground
inflow at 13m (top of rock)
major inflow at 27m (fault)
inflow at 37m (fissure)
inflow at 44m (fissure)

Figure 2a. Pumping test at Ballyferriter, Co. Kerry, showing influence of location of main inflows

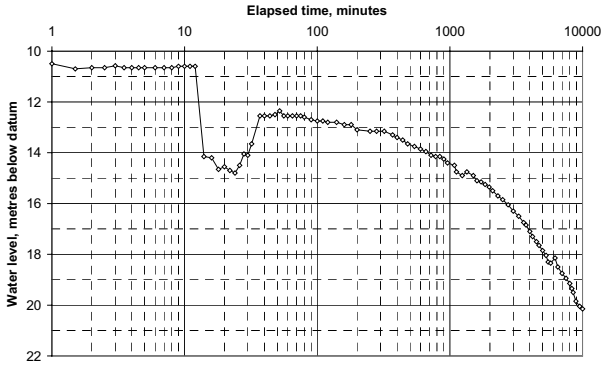

Figure 2b. Kilknockan pumping test, 18-29/9/89 – continued drawdown after 11 days

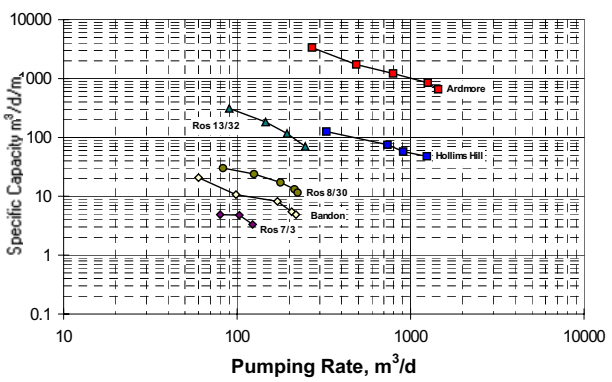

Figure 3. Selected step tests in unconfined fractured aquifers

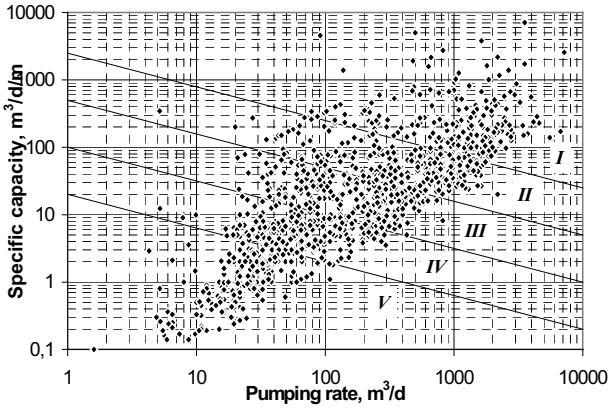

Figure 4a. Q/SC graph for whole data set, showing thresholds between Productivity classes I to V

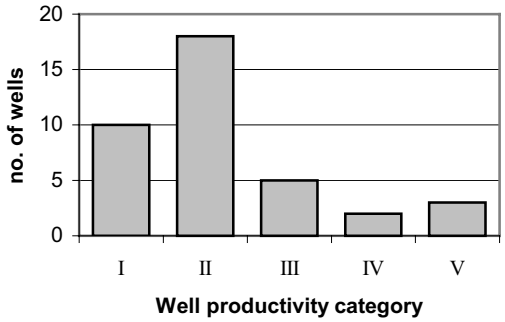

Figure 4b. Q/SC profile for major fractured aquifer

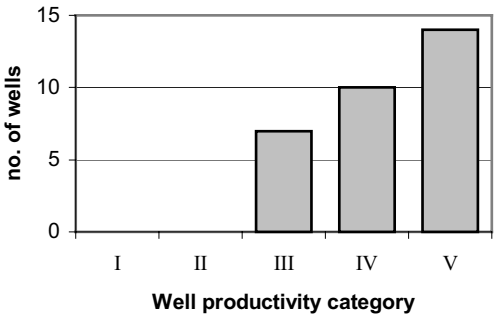

Figure 4c. Q/SC profile for poor fractured aquifer

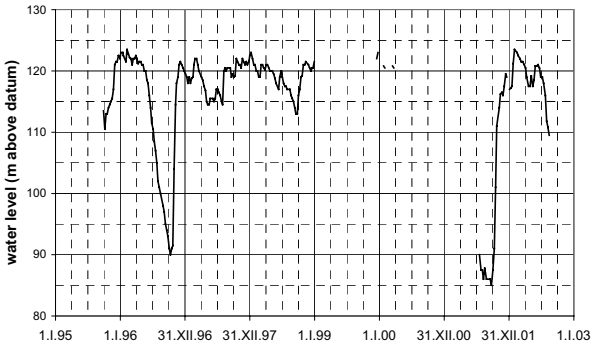

Figure 5. Hydrograph of production well at Templemore, showing excessive drawdown in dry years

TOPIC 2

GROUNDWATER FLOW AND RESOURCES IN FRACTURED ROCKS

- Natural, induced and artificial recharge
- Flow in fractured rocks
- Groundwater runoff, interrelation between surface water and groundwater
- Spatial and temporal changes of groundwater regimen, climate changes

Managing weathered-fractured aquifers in a semi-arid region under monsoon climatic conditions in India

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A b s t r a c t : In crystalline hard rock regions, the two aquifers zones viz., weathered and fractured with quite different properties are coupled through a mixed zone and are not separated by any aquicludes. This makes the system complex for understanding its structure and functioning. The Indo-French center for Groundwater Research at Hyderabad, India has taken up such an aquifer system and carried out detailed investigations to determine the parameters of the aquifers, conceptualize the flow conditions, simulate the flow in weathered-fractured coupled system and analyse the effectiveness of artificially recharging the deeper aquifer. The semi-arid and monsoon climatic conditions with over-exploitation has changed the water resources scenario in such an aquifer system and made the weathered zone unsaturated with flows mainly taking place in the fractured zone. An intensive monitoring and a variety of experiments viz., geophysical, geological, geohydrological, hydraulic and numerical modelling has helped in understanding the structure and behaviour of the aquifer system, characterize the representative parameters and assess the potential with the water balance of the system.

INTRODUCTION

The Indian sub-continent is underlain by Archean basement i.e. hard rock formations that are devoid of primary porosity and occupy more than 2/3 of the landmass. The climate is semi-arid with an annual precipitation of about 800 mm. Gustafson and Krásny (1994) proposed that the term “hard rock” might, from a groundwater exploration point of view, include all rocks without sufficient primary porosity and conductivity for feasible groundwater extraction. Globally there is a common feature of these rocks that they under the influence of pressure, temperature and rock-aquifer interactions tend to become weathered at shallow levels, semi-weathered and fissured at intermediate levels and fractured at deeper depths. Thus these hard rocks in general consist of two zones viz., the weathered and the fractured that may be separated through a semi fractured layer. The fractured zone ends up in massive hard rock at deeper levels of about 40 to 50 m. Due to the adaptation of latest drilling technology in India during the last few decades, groundwater has been exploited on a large scale. This uncontrolled exploitation of the source has resulted in declining water levels in wells. Presently the situation is very alarming since the weathered zone of 12 to18 meters has become mostly dry in many parts of the country. The circulation of groundwater in these rocks is dependent upon various processes that exhibit variant properties

A closed watershed of 55 Km^2 in south of Hyderabad, India has been selected considering a number of scientific and logistic parameters as a pilot area for research (Fig.1). Under various national and International programs it has been equipped with variety of monitoring and experiments that are highlighted here to discuss the management of groundwater in a weathered-fractured coupled system lying in a semi-arid condition and subject to the monsoon climate.

FIELD INVESTIGATION AND INTERPRETATION

Geophysical Investigations

A combination of geophysical methods viz., electrical imaging, mise-a-la-masse resistivity profiling as well as sounding and magnetic could provide geometry of the aquifer, thickness of the fractured zones and also the extent of the fractures. The Self Potential method jointly with measuring the potential distribution under Mise-a-la-masse technique could indicate the direction and extent of the fractures that have been encountered in the bore well (Kumar *et al.* 2003). A number of dolerite dykes present in the area were characterized by the magnetic survey and geophysical profiling with different electrode separation.

Hydraulic tests

The characterization of the hydraulic properties of the weathered-fractured layer is carried out using hydraulic tests at different scales: slug tests, flow measurements during injection and pumping tests. The latest are interpreted using specific methods to fractured media - anisotropic, double porosity, single fracture and fractional dimension flow models - leading to characterize the geometry and hydraulic properties of fracture networks and blocks. Two secondary networks of fractures are identified. A main network of horizontal fractures is responsible for the sub-horizontal conductivity of the weathered-fractured layer. A second network of less permeable subvertical fractures insures the connectivity of the aquifer at the borehole scale. The vertical anisotropy ratio is close to 10 (Maréchal *et al.* 2003). A primary network of fractures contributes to increase the permeability and storage of the matrix in the blocks. Results are compiled in a hydrodynamic model. Finally, it is shown that the weathering process is at the origin of fracturing and hydraulic properties of the aquifer.

Geostatistical Analyses

The aquifer parameters including water levels and water quality were analyzed geostatistically through variographic analyses. It has also been possible to evolve common variogram(s) for different time periods that helps making estimation of the water level without involving the cumbersome process of variographic analyses each time. Geostatistical methods of estimation variance reduction could prepare the optimal water level monitoring network and it was shown that out of 57 wells only 40 could be sufficient to obtain the same regional picture of the water levels (Ahmed 2002). This exercise has helped in avoiding some of the wells fitted with pumps.

Groundwater budget and Aquifer Modeling

A two layered numerical model, first layer representing the weathered aquifer and the 2nd for the fractured-fissured aquifer has been prepared using Integrated finite difference approximation with the code MARTHE developed at the BRGM, France. Initially the model has no flow from the boundaries following the surface topography with small outflow at the northern tip. The up-scaled hydraulic parameters have been assigned to each mesh after estimation. Various intrusive are to be considered carefully e.g.; as conduits in the weathered layer but as barriers in the fractured layers and compartmentation of the aquifer has been common and at times provided a better calibration. The semi-arid condition with over exploitation has resulted in a rapid water level decline. In such a condition,

estimation of recharge is important as the rainfall recharge through unsaturated zones including weathered zones are negligible compared to the preferred path recharge. The water-balance and simulation of flow shows a consistence and uneconomic water level decline in the area in the future.

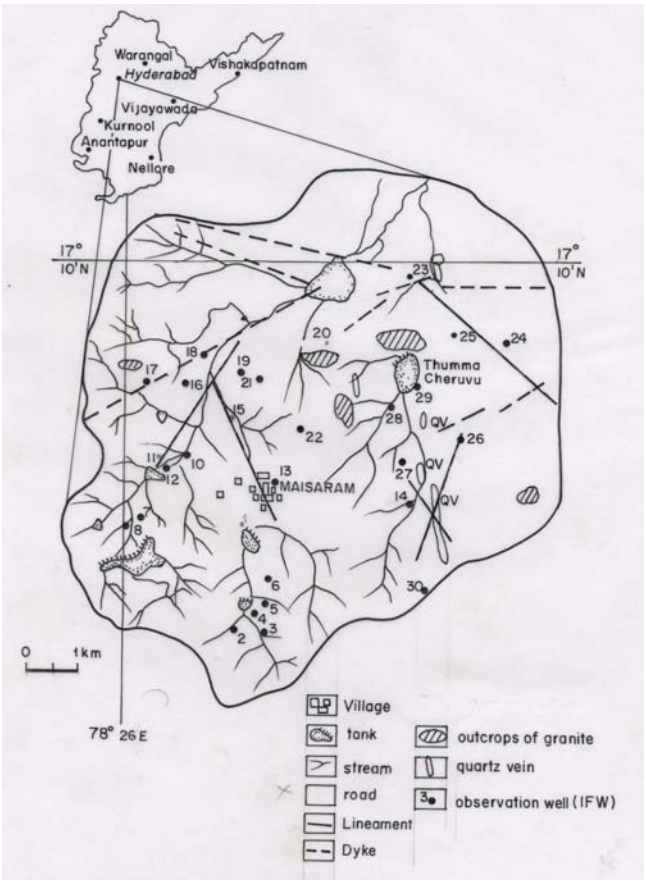

Figure 1. Location of the study area with drainage and structural features with monitoring wells

AUGMENTATION OF WATER RESOURCES THROUGH ARTIFICIAL RECHARGE

Wide variability in the rainfall has been observed and hence very close measurements has been suggested have been suggested using the local villagers. However, with the alarming misbalance of water resources in the area, the prevailing semi-arid conditions and due to fact that the number of rainy days are limited to around 50 per year during the monsoon, it is necessary to capture the runoff water to recharge the aquifer. It is found that artificially recharging the aquifer through defunct dug wells is more viable and cost-effective than through the thickly silted tanks. A few dug wells having larger catchment area have been selected and equipped with a pit to remove the silt and eroded material and then the stored water is sent to the dug well. The dug well bottom have been tested for the infiltration rates. Thus the recharge have been quantified and the advantages include the reduced evaporation losses and higher infiltration from even the walls of the well that often have horizontal fractures, compared to the surface tanks (Fig.2).

CONCLUSIONS

The hard rock hydrogeology is beset with more uncertainties rather than any proven thumb rule solutions. An over-exploited area in a granitic terrain in India, has been studied for the groundwater flow patterns and estimation of groundwater potential. The area has been thoroughly investigated with respect to inventory of wells, extent of geological outcrops, the depth and yield of wells, measurement of structural orientations, lithology and geo-electrical studies. The SP technique was useful in reducing the number of resistivity soundings. The results of all these studies show that the granitic terrain has been subjected to different episodes of granite emplacement that has given rise to differential weathering, causing heterogeneity in the rock matrix. Application of geostatistical techniques made it possible to minimize the number of observation wells for the same output of seasonal fluctuations. The pumping test analyses show a wide disparity in results with a transmissivity variation of 30 to 240 sq m /day and low storage coefficient. A very important feature observed is that the water levels vary drastically in a day, apparently not influenced by any nearby pumping. The possible reasons for this feature are being studied. The study highlights the priority and usefulness of certain investigations providing crucial data and at the same time suggests that some experiments could be reduced or avoided.

REFERENCES

Ahmed S (2002) Groundwater monitoring network design: applications of geostatistics with a few case studies from a granitic aquifer from semi-arid region in a semi-arid region, In: Sherif M.M. *et al* (eds) Groundwater Hydrology 2:37-57, AA Balkema Publishers

Kumar D, Krishnamurthy NS, Ahmed S, Jain SC, Dhar RL (2003) Mise-à-la-Masse (Charged Body) technique in establishing the lateral extension of fractures in hard rocks. Jour. of Geological society of India 61(2):185-194

Gustafson G, Krásny J (1994) Crystalline aquifers: their occurrence, use and importance. Applied Hydrogeology 2(2):64-75

Maréchal JC, Wyns R, Lachassagne P, Subrahmanyam K, Touchard F (2003) Anisotropie verticale de la perméabilité de l'horizone fissure des aquifers de socle: concordance avec la structure géologique des profiles d'altération, C.R. Geoscience 335:451-460

Interpreting the evolution and stability of groundwaters in fractured rocks

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A b s t r a c t : Geochemical and isotopic data from groundwaters in fractured rocks in the UK and Scandinavia are reviewed to illustrate the interpretations of evolution and stability and the limitations due to sparseness and reliability of data and interpretative uncertainties. This paper assesses the significance of these data for the various factors that have affected evolution and stability and that might distinguish groundwater systems in different areas or regions.

INTRODUCTION

Groundwaters in fractured rocks with low permeabilities are likely to have a longer 'history' than groundwaters in more permeable aquifers. Such rocks have relatively slow rates of groundwater movements and heterogeneous hydrogeological properties. Topographic heads which drive lateral water movements usually decline with depth and transit times are longer, resulting in varying degrees of vertical stratification of water masses and sometimes of densities. Lateral variations of these patterns indicate the extent to which fracturing has compartmentalised groundwaters so that they have evolved by local water movements rather than regional flows.

The evolution and stability of such groundwater systems are of interest for a number of reasons. Understanding how groundwaters evolved to the present state involves two questions about flow: the relative importance of lateral and vertical water movements (and lateral vs vertical connectedness of fracture networks), and whether the system has been stable over time with respect to conditions at its boundaries. These issues have implications for water resources development, contaminant movement and long-term safety of waste disposal in fractured rocks. Understanding them helps to develop a conceptual model for groundwaters in fractured rocks. They are characterised by geochemical and isotopic variations that identify site-specific water compositions and transit times, given sufficient reliable data,.

Calculations using ranges of values for hydraulic conductivity and porosity that are appropriate for these rocks, and lateral hydraulic gradients that are typical for hard rock terrain, show that transit times for water over km-scale distances are likely to exceed 10^4 years. Similar estimates for vertical water movements using gradients typical of infiltration conditions (e.g. seawater intrusion) indicate that transit times at 100m-scale are in the order of 10^3 years. A weathered zone (typically 100 m thick) which is more transmissive has a significant influence on vertical and lateral water movements in deeper fractured rock.

The content of ^{14}C should therefore be a useful indicator of recharge and lateral flow in such rock formations. Although the actual transport and observed decay of ^{14}C (as bicarbonate ion) potentially involves dispersive mixing, 'dilution' by dissolved carbonate, and matrix diffusion, ^{14}C data indicate the general time scales of water movements.

GEOCHEMICAL AND ISOTOPIC DATA

There are only few ^{14}C data for groundwaters in fractured rocks in Britain (Fig.1). Groundwaters from boreholes at Altnabreac (≤270 m) and from springs in mid-Wales have ^{14}C values corresponding to average ages around 12,000 and 5,000-10,000 years respectively. They have only small negative shifts of $^{18}O/^{16}O$ ratios and thus only small components of 'cold climate' recharge, i.e. infiltration during or at the end of the last glaciation.

Inflow samples from mine workings at 690 m depth in the Carnmenellis granite in south-west England are mixtures with very old saline water because the regional lateral gradient has been changed by drawdown of young water and upconing of thermal saline water towards the mine workings. Groundwaters between 76 and 485 m depth in a borehole into outcropping basement rock at Sellafield become more saline with increasing depth and have ^{14}C contents and $^{18}O/^{16}O$ ratios indicating ages of 10,000-18,000 years, i.e. post-glacial. These groundwaters are younger than saline groundwaters at greater depths in basement rocks beneath sedimentary cover rocks at Sellafield that have 'cold climate' $^{18}O/^{16}O$ ratios.

In Shield rock in Sweden and Finland, fresh water typically extends to at least 100 metres depth in outcropping fractured rocks, though brackish water is found at shallower depths in coastal locations, especially where isostatic seawater intrusion has occurred during the early Holocene. ^{14}C data indicate that deeper (≤900 m) groundwaters generally have average ages around 10,000-20,000 years (Fig.1). $^{18}O/^{16}O$ data indicate that some of the deepest waters may be cold climate recharge up to 30,000 years old.

Brackish waters at 100-500 m depth at Äspö (a coastal site) have low ^{14}C contents (<25 pmC) and originate from a 'palaeo-Baltic' seawater mixed with older cold climate fresh water. Other brackish waters down to 200m depth have 25-70 pmC ^{14}C and are mixtures of modern Baltic water with older and younger meteoric waters.

Olkiluoto in Finland is also coastal and palaeo-Baltic brackish water penetrated the system to at least 700 m depth, mixing with older brackish/saline water. Though some ^{14}C contents are low (10-25 pmC), ^{14}C data are mostly between 30-60 pmC indicating mixing with post-glacial meteoric water. Isotopic and chemical data for these coastal sites indicate that vertical groundwater movements have been controlled by the sequence of palaeo-Baltic salinities over the last 8,000 years or so, leading to rather heterogeneous stratification and varying amounts of in-mixed relict cold climate meteoric water.

DISCUSSION

Some interesting points emerge from these data and the inferred ages and compositional variations for groundwaters in these different areas in northern Europe. Firstly, there are few ^{14}C measurements that are near or below detection limit (i.e. >35,000 years old). Though possibilities of contamination have to be considered, this suggests that lateral flow paths are not very long and that groundwaters at the depths investigated in these regions originated predominantly during and since the last glaciation. Secondly, the lateral continuity or heterogeneity of water compositions in some cases is indicative of a rather high degree of compartmentalisation by fracture zones. Shallow groundwaters with low ^{14}C contents (i.e. old water) occur near to the end of flowpaths along relatively high topographic and hydraulic gradients, probably having less vertical fracturing and perhaps transmissive sub-horizontal fracture zones. Thirdly, in areas where past sea level changes have caused intrusions directly into exposed fractured rock, groundwater stability during the Holocene has depended on the secular variations of salinity/density for infiltrating water and on the heterogeneity of

vertical flow paths provided by fracture zones. Stratification of groundwaters with increasing salinities and densities, which gives a groundwater system increasing stability with increasing depth, depends on the interplay between inflows along vertical gradients, compartmentalisation by fracture zones, and lateral interconnection.

CONCLUSION

Given sufficient reliable data to interpret spatial variability, patterns of isotopic and hydrochemical variations should assist in constructing groundwater flow models that give coherent explanations of present flow and past evolution in terms of site-specific characteristics. This type of approach to palaeohydrogeology, based on chemical and isotopic data for groundwaters, is complementary to using secondary mineralisation in fractures as a direct record of past geochemical conditions and as indirect evidence of past water movements and mixing (e.g. Bath *et al*., in press).

REFERENCES

Bath A, Milodowski A, Tullborg, E-L, Kärki A, Ruotsalainen P, Shepherd T, Cortés Ruiz A, Aranyossy J-F Submitted to Chemical Geology. Palaeohydrogeological information from secondary calcite in fractured rocks at European sites

Darling WG, Edmunds WM, Smedley PL (1997) Isotopic evidence for palaeowaters in the British Isles. Applied Geochemistry 12:813-829

Edmunds WM, Andrews JN, Burgess WG, Kay RLF, Lee DJ (1984) The evolution of saline and thermal groundwaters in the Carnmenellis Granite. Mineralogical Magazine 48:407-424

Edmunds WM, Robins NS, Shand P (1998) The saline waters of Llandrindod and Builth, central Wales. Journal of the Geological Society of London 155:627-637

Feast N, Bath A (1997). Evaluation and interpretation of carbon isotope and tritium data for groundwater samples from deep boreholes at Sellafield. Nirex Report SA/97/094. UK Nirex Ltd., Harwell

Fritz P, Fontes J-Ch, Frape SK, Louvat D, Michelot J-L, Balderer W (1989) The isotope geochemistry of carbon in groundwater at Stripa. Geochim Cosmochim Acta 53:1765-1775

Kay RLF., Andrews JN., Bath AH, Ivanovich M (1983) Groundwater flow profile and residence times in crystalline rocks at Altnabreac, Caithness, UK. In: Isotope Hydrology 1983, pp 231-248. International Atomic Energy Agency, Vienna

Pitkänen P, Luukkonen A, Ruotsalainen P, Leino-Forsman H, Vuorinen U (1999) Geochemical modelling of groundwater evolution and residence time at the Olkiluoto site. Report Posiva 98-10. Posiva Oy, Helsinki

Smellie J, Larsson N-Å, Wikberg P, Carlsson L (1985) Technical Report 85-11, SKB Stockholm

Smellie J, Laaksoharju M (1992) The Äspö Hard Rock Laboratory: Final evaluation of the hydrogeochemical pre-investigations in relation to existing geologic and hydraulic conditions. Technical Report 92-31, SKB Stockholm

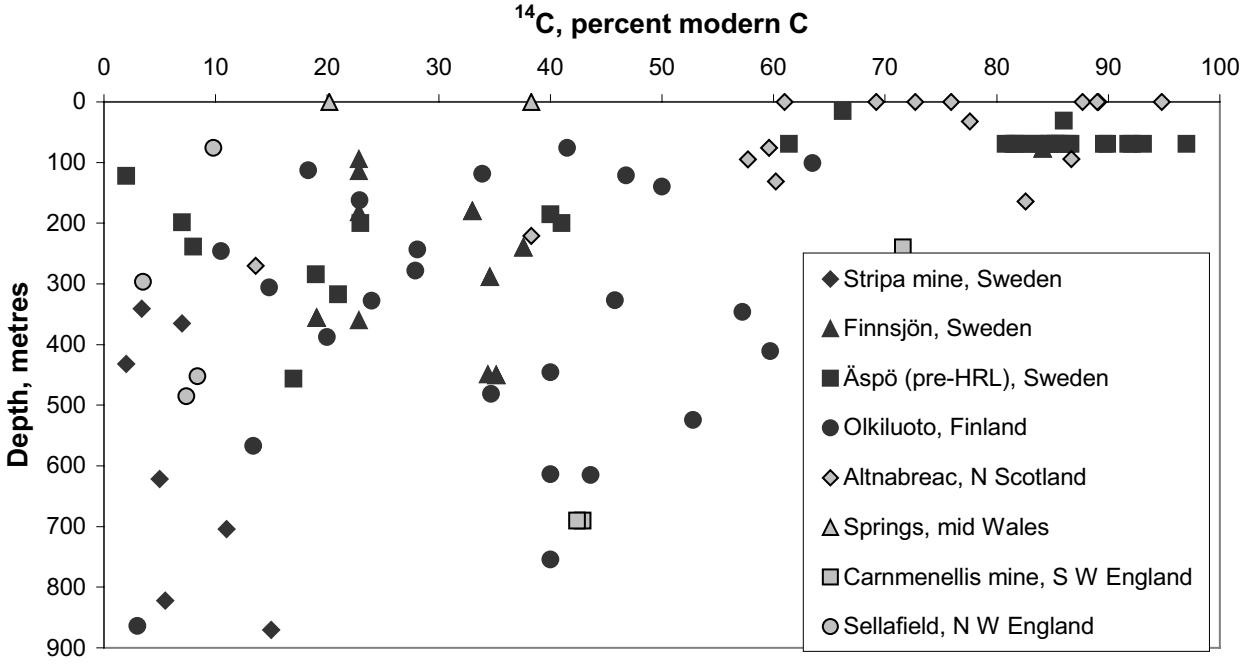

Figure 1. Carbon-14 contents of groundwaters in fractured rock formations in Britain and Scandinavia (data from Kay *et al.* 1983, Edmunds *et al.* 1984, 1998, Darling *et al.* 1997, Feast and Bath 1997; Fritz *et al.* 1989, Smellie *et al.* 1985, Smellie and Laaksoharju 1992, Pitkänen *et al.* 1999)

Prediction of runoff changes in hard-rock regions using CUTTOS simulation tool

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Abstract: Besides quality water quantity is an important factor for water management. Especially in hard rock areas information of available reservoirs in catchments are of main importance. One task of EU-project LOWRGREP are investigation to evaluate runoff changes in local scale. To simulate runoff conditions simulation tool CUTTOS (developed by university of Zaragoza) was tested at the German LOWRGREP region "Lehstenbach catchment" (Fichtelgebirge, NE-Bavaria). To simulate the local runoff decreasing parts of discharge curves were used to adjust an mathematical equation. Calculated results allow 1) determination of different kinds of reservoirs and 2) monitoring of dynamic changes in the ration of different flow types.

INTRODUCTION

For local water supplies in hard rock areas it is necessary to gain information about the different available reservoirs. As part of 5th framework EU-project LOWRGREP (Landscape-use Optimisation With Regards of the Groundwater Resources Protection in the mountain hardrock areas) detailed investigations focus on the evaluation of runoff changes in local scale. To simulate temporal variations of runoff conditions the Spanish LOWRGREP-partner from University of Zaragoza developed CUTTOS 2.0 simulation tool (Navarro Sánchez 2002) which was tested with data base from "Lehstenbach catchment".

LEHSTENBACH CATCHMENT

The smallest German LOWRGREP test region (4.19 km^2) is located in the mountainous region of the Fichtelgebirge (N-Bavaria) approximately 30 km north-east of the city of Bayreuth (fig.1). Annual precipitation rates are approximately 880 mm/a with an evapotranspiration between 450 and 490 mm/a. Land use is predominantly forest (73% spruce, 27% mixed forest mainly spruce). Due to intensive weathering recently the regolith reaches depths up to 40 m. One third of the catchment is covered by pseudogleyes, dystic histosols and moors. These wet zones are drained by artificial created ditches. Main groundwater flow is bound to shallow porous aquifers. Flow through fractures is of minor importance (Lischeid *et al.* 2001).

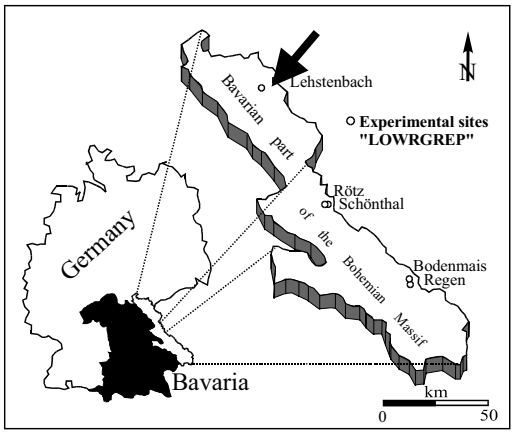

Figure 1. Locations of the German LOWRGREP test sites (Bender *et al.* 2001)

Due to several research projects done by the German steering group partners Bavarian State Office for Water Management (BayLfW) and Bayreuth Institute for Terrestrial Ecosystems Research (BITÖK) there exist a lot of hydrological information. Since 1987 surface runoff is measured continuously at a official weir of the BayLfW "Zigeunermühle (Waldstein)", whereas discharge rates represent more or less total runoff of the catchment. Average discharge ranges between 20 and 25 L/s. Maximum values are the result of thawn (up to 500 L/s) and thunderstorms (up to 300 L/s), minimum values (approx. 10 L/s) appear during dry seasons.

CUTTOS SIMULATION TOOL

Generally temporal curves of hydrographs show impacts of precipitation events and melting of snow as well as dry seasons. Using programme CUTTOS 2.0 it is possible to separate runoff conditions into component controlled surface runoff, interflow and baseflow. The principle of the program is based on a black box model (operations of the whole aquifer) using an evaluation of upward sections of the hydrograph. This slope of the graph is characteristic for draining behaviour of the reservoir and therefore for regulation capacity of the ground. For simple aquifer situations dry weather flow curves are fitted to exponential equations. Regression curve can be described by a simple exponential function: $Q_t = Q_o e^{-\alpha * t}$ with (Q_t=discharge at time t in [m^3/s]; α = empirical coefficient (drying coefficient from Maillet)). Mostly total runoff of brooks and rivers are influenced from direct runoff from more than on aquifer system.

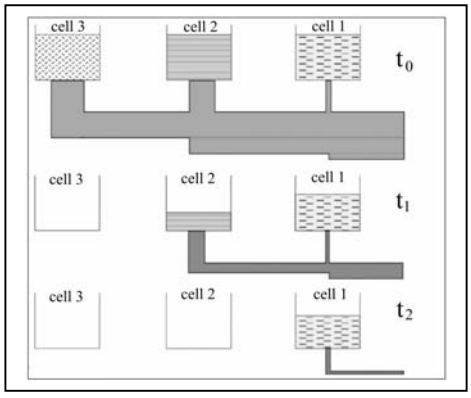

Figure 2. General scheme of CUTTOS structure (Navarro Sánchez 2002)

To separate runoff components the program uses resolution method suggested by Schoeller (1965). In case of a complex aquifer systems (fractured aquifers, decreasing flow conditions) hydrograph curve is a sum of different curves of recession, where each discharge regime (cell) can be calculated by fitting all parts of a multi-cell-model ("pluricellular enclosed") to the curve to

obtain Q_0 and α of each "cell". Using three different cells it is possible to describe the diminution of flows of any hydrological system (fig.2). The sum of dynamic volumes of each cell is approximately the total dynamic volume of the hydrological system. Knowledge of temporal development of flow and dynamic volume allow an estimation of effective recharge of the system as well as simulation and prediction of the contribution of flow parameters. At the start of calculation ($t=t_0$) discharge rate is at maximum. Water is flowing from three different reservoirs. At $t=t_1$ discharge of cell 3 becomes irrelevant. Total runoff contributes from cell 1 and cell 2 only. Later ($t=t_2$) whole flow is controlled by cell 1 (base flow conditions). Regarding hydrograph curve of this discharging process the linear fitting of the segment for base flow conditions gives the parameters for cell 1.

The difference between actual flow conditions (Q_{real}) and results of the fitted line (Q_{cell1}) builds a new curve of recession flows. At the end of curve segment a new linear fitting result for parameters of cell 2. The same has to be done for cell 3 to fit the start of hydrograph curve (fig.3). The comparison of $Q_{estimated}$ ($Q_{cell1} + Q_{cell2} + Q_{cell3}$) and Q_{real} shows nearly same values. Total volume of water stored in a hydrological system builds the dynamic volume for discharge (springs) or flow rates. The sum of dynamic volumes of all cells (total dynamic volume) is an useful parameter to compare different hydrodynamic regimes. Generally high dynamic volumes are typical for bigger catchments and fast decrease of flow rates is a hint for a lower regulating capacity as a result of a small impact of base flow.

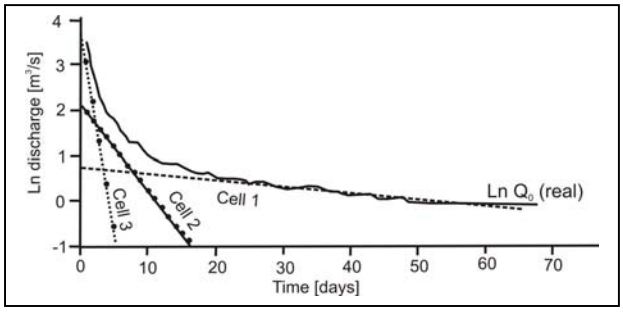

Figure 3. Fitting segment cells

CUTTOS-APPLICATION

Regarding runoff conditions in dry periods (basic runoff) discharge was never below 0.25 mm/d (BITÖK 1998). Temporal variation of runoff reacts sensitive on precipitation events. Lischeid *et al.* (2001) observed an increase of discharge after heavy rain events within a few hours up to a multiplier of 20, whereas the peak of runoff curve is usually observed 2-4 hours after maximum in precipitation. After short time events lasting from a few hours up to two days huge parts of precipitation are drained quickly by surface runoff. For application of CUTTOS simulation tool only decreasing parts of discharge curves are used. As an example simulation results using a regression curve of summer period 28.06.91-10.07.91 allow a determination of three different reservoirs for runoff (fig.4). Discharge of cell 3 (direct surface runoff) is decreasing very fast and disappeared within three days. Water flow of shallow interflow water (cell 2) is predominant parameter from second until fourth day. After the fifth day base flow (cell 1), which is mainly fed by groundwater recharge, builds main source for measured runoff. Due to small size of the catchment (419 ha) dynamical changes in the ratio of different flow types are relatively fast. This is reflected by a dynamic volume-discharge relation for small dynamic volume. Comparison of volumes of reservoirs confirm the dominating character of base flow (85%). Both other reservoirs are of same importance (surface runoff 8% and interflow 7%). All results confirm the low recharge rates of 4 L/(s*km2) due to high relief and loamy covering layers, which prevents an infiltration and storage of precipitation (Rüdiger and Wohnlich 1995).

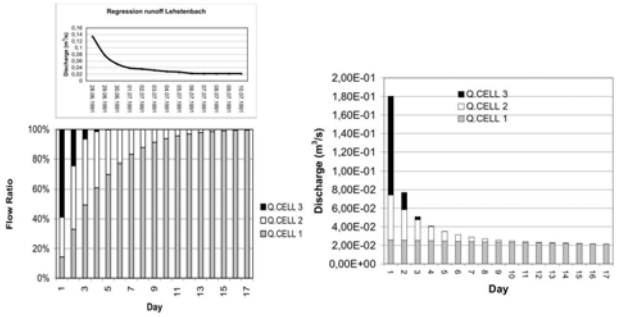

Figure 4. Results of CUTTOS 2.0-simulation

CONCLUSION

Due to existing long term data of runoff rates the German LOWRGREP test region Lehstenbach catchment was choosen to test CUTTOS 2.0 simulation tool. Simulated results are plausible and reflect the typical local hydrogeological situation. Since most of significant recession appear during few hours, events with a long tailing slope (slow outflow of reservoir) can be used, only. Through division of recession curves in a semi-logarithmic scale, the ruoff can be divided into parts from different "reservoirs", which are feeding surface runoff of a river or brook. In a three-cell-model runoff information are separated into surface runoff, interflow and base flow.

ACKNOWLEDGEMENTS

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REFERENCES

Bender S, Vornehm Ch, Wohnlich S, Lautenschlager T (2001) Scheme for developing a GIS-based data bank in the region of Regen (E-Bavaria). In: Seiler KP, Wohnlich S (eds) New Approaches Characterizing Groundwater Flow - Proc XXXI IAH-Congress 907-909

BITÖK (1998) BITÖK Forschungsbericht 1995–97. Bayreuther Forum Ökologie 56, 256 pp

Lischeid G, Moritz K, Bittersohl J (2001) Hydrogeologie im Einzugsgebiet „Lehstenbach". In: Gerstberger P (ed.) Bayreuther Forum Ökologie 90:91-101

Navarro Sánchez JA (2002) Decomposition of baseflow recession curves in basins formed mainly by hard rocks. CUTTOS 2 Pluricellular Model.- LOWRGREP-Project User Manual, 14 pp

Rüdiger F, Wohnlich S (1995) Hydrogeological investigations in the Lehstenbach catchment area, Fichtelgebirge. Acta Universitatis Carolinae: Geologica 39:159-166

Schoeller H (1962) Les eaux souterraines, 642 pp

An experimental study of groundwater recharge to fractured bedrock

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A b s t r a c t : The interchange between the groundwater in a till soil and the underlying crystalline bedrock is studied at a site in central Sweden. Groundwater head is measured at different depths in two boreholes in the bedrock and in piezometers in the till. There are also ongoing long-term continuous measurements of for example precipitation, evapotranspiration, and profiles of temperature and water content in the soil. The area is flat, but the small-scale topography and the head difference between soil and rock indicate that the area is a possible local recharge area for bedrock groundwater. The goal of the project is to develop a conceptual model and a mathematical model of the interchange between soil and bedrock groundwater in the area, which can lead to a better general understanding of groundwater recharge to bedrock.

INTRODUCTION

Groundwater in fractured bedrock is an important water resource for domestic water consumption in many regions of the world. The groundwater recharge is a key factor for sustainable management of the groundwater resources in the bedrock, e.g., for assessments of impacts of water withdrawal or underground constructions. The groundwater recharge to superficial soil aquifers can in many cases be determined with a fair accuracy from water balance considerations, i.e., from measured precipitation and calculated evapotranspiration (de Vries and Simmers 2002). The recharge to the underlying bedrock is more difficult to quantify. It is controlled by the hydraulic potential difference between the soil and bedrock aquifer and the hydraulic properties at the interface.

In this project, groundwater recharge to fractured bedrock is studied at a site in central Sweden. The goal is to develop a conceptual model and a mathematical model of the interchange between soil and bedrock groundwater in the area, which can lead to a better general understanding of groundwater recharge to bedrock.

MEASUREMENTS

The study is performed north of Uppsala, Sweden, at the Norunda Central Tower Site of the NOPEX project (Lundin et al., 1999). The area is flat, with small-scale variations in altitude up to 10 m. The bedrock consists of granite, sedimentary gneiss, and leptite. The soil is a compact sandy-loamy till with a high content of stones and blocks. The site is forested, and spruce (*Picea abies*) is the dominating species. At the site, there are ongoing long-term continuous measurements of for example precipitation, evapotranspiration, and profiles of temperature and water content in the soil (Lundin *et al.* 1999).

The installations for the groundwater recharge study were done in spring 2002 at a low hill that was interpreted as a possible groundwater recharge area. The soil cover was 10-15 m deep at this place. Two boreholes were drilled into the bedrock to a depth of 40 m (Bh C) and 50 m (Bh A) below the ground surface. In both boreholes, one zone was found to totally dominate the transmissivity of the borehole. It was located 16 m below the ground surface, just below the bedrock surface, in Bh A, and at 32 m in Bh C. Borehole C was sectioned using inflatable packers. Furthermore, a number of groundwater tubes and piezometers were installed at various depths in the till.

Groundwater head is continuously logged in the two boreholes in the bedrock and in the piezometers in the till. The activities also include sampling of groundwater for analyses of chlorofluorocarbons (CFCs) and tritium. The tracers will be used for dating of the groundwater and validation of the model.

EXAMPLE OF RESULTS

The initial measurements concerned mainly undisturbed conditions. A vertical hydraulic gradient was observed both in the soil and the bedrock. The difference in elevation between the water table in the soil and the head in the fracture zone at 32 m in Bh C was about 3 m, with an increased gradient at recharge events (fig.1). The head difference between soil and rock indicate that the area is a local recharge area for bedrock groundwater.

REFERENCES

De Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. Hydrogeol J 10(1):5-17

Lundin L-C, Halldin S, Lindroth A, Cienciala E, Grelle A, Hjelm P, Kellner E, Lundberg A, Mölder M, Morén A-S, Nord T, Seibert J, Stähli M (1999) Continuous long-term measurements of soil-plant-atmosphere varables at a forest site. Agric For Meteorol 98-99:53-73

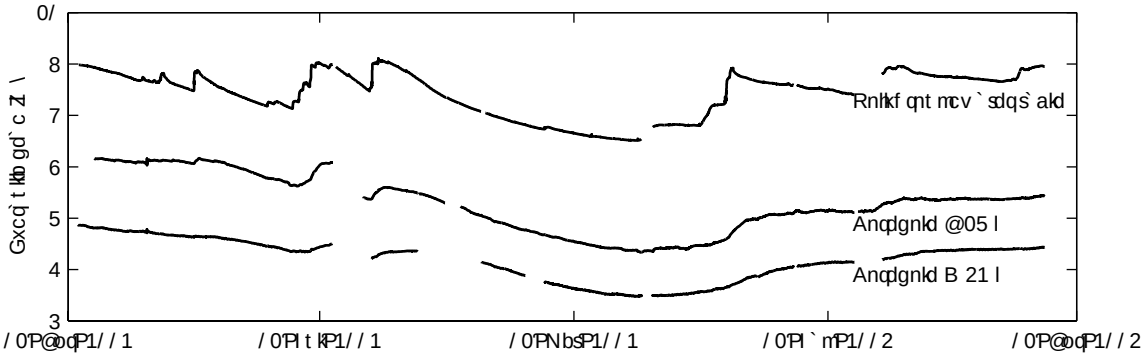

Figure 1. Time series of the water table elevation in the soil and the hydraulic head in the bedrock at 16 and 32 m below ground surface

Non-Darcian two-phase flow in fractured rocks

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A b s t r a c t : The paper briefly recalls the main cases in which the two-phase flow do not follow the classical extension of Darcy's law to multiphase flow, taking into account those which are found in hydrocarbon reservoirs and which, with suitable modifications, may be found in geohydrology as well. It is pointed out that both porous media and fractured rocks may have very different features: the former range from cemented sandstones to sand or gravel, while the latter can have fractures with widths ranging between a few microns and several centimeters. In both cases, the dimensions of the flow channels – and hence the ratios among the force present – may be very different. To conclude it would therefore be interesting to carry out a differentiated study on flow laws based on the values of the ratio between viscous, gravitational, inertial and capillary forces, rather than on the distinction between porous media and fractured media.

INTRODUCTION

Until a few years ago, the study of underground multiphase flow was mainly of interest for Reservoir Engineering and Geothermy. However, this study has recently acquired importance in presence of gas or in the case of aquifer pollution by non aqueous phase liquids (NAPLs).

Depending on the circumstances, the fluids may have very different characteristics, and different may be the characteristics of the rocks where they flow: from porous media (unconsolidated or cemented) to fractured rocks (with fractures ranging from microfractures of a few microns, to megafractures which can cover thousands of metres and can have openings sometimes several centimetres wide). Consequently, the factors which affect flow can weight differently in different situations, giving rise to different laws of flow.

At first sight, it would seem obvious that there are different models for flow in porous media and in fractured rocks; it can be seen, however, that the laws of flow are decisively affected, not only by the features and velocity of the fluids, but also by the size of the flow paths, a size which may be more similar between a porous medium and a fractured rock than between two very different porous media or two fractured rocks. For example, the flow in a rock with fractures having openings of several millimetres is more similar to the flow in gravel than to that in a rock with microfractures.

So, we believe it is more suitable to examine the flow in fractured rocks and in porous media in a unitary fashion, based on the size of the flow paths or, rather, on the weight of the present forces: viscous, gravitational, inertial and capillary.

This feature is especially suitable in the case of flow which does not follow Darcy's law, extended to multiphase flow, i.e., where the capillary forces are not prevalent compared to all the others, and the inertial forces are not negligible compared to the viscous forces.

Several studies have been carried out by now on this topic; however, due to the complexity of the phenomenon, it has not yet been possible to identify generally valid relations, but only empirical relations having limited validity. In many cases, the very dynamics of the phenomenon are not clear.

FORCES OF INERTIA NOT NEGLIGIBLE COMPARED TO VISCOUS FORCES

It has been known for over a century that, in the case of single phase flow both in porous media and in fractures, in laminar flow, but at high speed, Darcy's law no longer applies, since it does not consider the inertial forces, in this case no longer negligible due to the continuous variations of cross section and to the winding nature of the flow paths. To be exact, in this case the potential drop is no longer linear function of the flow rate; many relations have been proposed, we shall use the relation of Forchheimer:

$$-grad\Phi = \frac{\mu}{\rho k} u + \beta u^2 \tag{1}$$

where u is the rate per surface unit of the medium, k the intrinsic permeability, Φ the Hubbert potential, ρ and μ the fluid density and viscosity and β is Forchheimer's coefficient, which depend on the permeability, the porosity and the winding nature of the medium.

In the case of two-phase flow, many empirical correlations have been proposed valid for both porous media and fractured rocks (with special reference to propped hydraulic fractures); for example, for the flow of both phases through beds of coarse particles, Schulenberg and Muller (1987) propose the following relation:

$$-grad\,\Phi_i = \frac{\mu_i}{k k_{ri} \rho_i} u_i + \frac{1}{\eta \eta_{ri}\, u_i} u_i^2 \qquad (i = 1, 2), \tag{2}$$

where $k_{ri} = k_i/k$ is the relative permeability of i-phase, while $\eta = 1/\beta$ and the η_{ri} are functions of the respective saturations S_i and also depend on the outflow paths.

COUPLING EFFECT

In the usual extension of Darcy's law to two-phase flow, the ratio of viscous to capillary forces is low, and one phase interferes with the flow of the other only insofar as it takes up part of the flow paths. This does not take into account the fact that both phases are flowing side-by-side in the porous medium and exert a reciprocal viscous drag that may affect significantly the flow of the contiguous fluid, hence, if they move at different speeds (in intensity, direction or verse), at the contact surfaces they deliver to each other tangential forces whose effect is all the more sensitive, the greater the ratio of viscous to capillary forces (Rose 1991). In this situation, the following relation is valid:

$$u_i = -(\lambda_{ii} grad\,\Phi_i + \lambda_{ij} grad\,\Phi_j), \tag{3}$$

where generally it is assumed to hold here reciprocity (or Onsager) relationship $\lambda_{ij} = \lambda_{ji}$, where λ_{ij} is the coupling coefficient, $\lambda_{ii} = \rho_{ii}\, k_{ii}/\mu_{ii}$ and $\lambda_{jj} = \rho_{jj}\, k_{jj}/\mu_{ij}$, with λ_{ii}, λ_{jj}, λ_{ij} to be determined experimentally.

This effect has been clearly highlighted in the case of flow in both porous and fractured media, where it has been found that the flows increase considerably when both fluids move in the same direction (cocurrent) compared to when the flows are countercurrent.

INERTIAL AND COUPLING EFFECTS

Mott, Cable and Spearing (2000), studying the flow of gas in the immediate neighbourhood of a gas-condensate well, where there is a strong saturation of liquid and where both gas and condensate move, found that at a high speed, there are two competing phenomena which make the effective permeability of the gas rate-dependent: i.e., the sum is made of the increase due to positive coupling or stripping velocity and the decrease due to the inertial effect. In this case, they have suggested introducing into equation (2) an effective permeability of the gas:

$$k_{g\,eff.} = k\, F_{nd}\, k_{rg}(S_g, N_c), \tag{4}$$

where F_{nd} (function of u_g) takes the inertial flow effects into account, while k_{rg} takes the coupling effect into account and is determined as a function of the saturation of gas S_g and of the capillary number N_c.

FOAMY-OIL FLOW

According to Darcy's law extended to two-phase flow, a fluid cannot move until it has formed a continuous phase, in this case the ratio between the flows of the phases depends on the ratio of the mobilities k_i / μ_i.

It has been seen that this does not happen in many reservoirs of viscous oil which produce by dissolved gas drive, where the wells produce a stable foam emulsion of gas in oil for a long time, and where the gas-oil ratio (GOR) is much lower than it should be according to Darcy's law, with a positive effect on the primary production of the reservoir (Maini 2001).

According to Maini, the different behaviour is associated not so much to supersaturation of dissolved gas in the oil, as to the distribution of the fluids in the medium: in fact, in the usual light oil reservoirs, the ratio of viscous to capillary forces is low and the distribution of the phases, which depends on the capillary forces, is the same under static and flowing conditions and is not influenced by the local pressure gradient. On the contrary, in this kind of reservoir, due to the high viscosity of the oil and to the high drawdown pressure used in cold production, the ratio of viscous to capillary forces is high and such as to mobilize the microbubbles (i.e., bubbles much smaller than average pore-throat size); an alternative hypothesis is that the larger bubbles can break during the migration with the oil. The phenomenon becomes easier to detect when the gravitational forces do not induce rapid segregation of the phases (i.e., when there is a high Bond number) and the pore-body/pore-throat ratio is small, as, for example, is the case of well sorted unconsolidated sands.

CONCLUSIONS

The considerations made in this paper highlight the fact that, for two-phase laminar flow in porous media, or in fractures, the generalized Darcy's law does not apply in cases where:
- forces of inertia are no longer negligible compared to viscous forces;
- the flow of one phase is influenced by the forces transmitted by the other phase across the contact surface (coupling effect);
- the distribution of the phases inside the medium does not depend so much on the capillary forces as on the viscous forces and gravity; a condition that takes place in foamy-oil flow when there is a high pressure gradient (and hence high speed). The same conditions generally takes place in the case of flow inside unconsolidated porous media or fractured media with small pore-body/pore-throat ratio, where there are different flow structures, depending on the speed of both phases and on the interface tensions.

In conclusion, it clearly appears that the flow model does not depend so much on whether the medium consists of porous or fractured rocks, but on the ratios between the forces present (i.e., on the Reynolds number, the capillary number and the Bond number). When such ratios vary, the flow models move over those which take place in a capillary network to models which take place in a network of pipes.

REFERENCES

Maini BB (2001) Foamy-oil flow. J Pet Tech53:54-64

Mott R, Cable A, Spearing M (2000) Measurements and simulation of inertial and high capillary number flow phenomena in gas-condensate relative permeability. In Proc. 2000SPE Annual Technical Conference and Exhibition, Dallas

Rose W (1991) Critical questions about the coupling hypothesis. J Pet Sci Eng 5:299-307

Schulenberg T, Muller U (1987) An improved model for two-phase flow through beds of Coarse Particles. Int J Multiphase flow 13:87-97

Transit time in karst conduits, saturated and unsaturated zone: tracer tests and isotopic methods

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A b s t r a c t : This study is focused on transit time in different parts of karst environment. Transit time in conduits was studied by tracer tests, transit time in other parts of saturated and unsaturated zone by environmental isotopes (^{18}O, tritium). There is a large difference between transit time obtained from tracer test compare to transit time obtained from ^{18}O and tritium, even on the same springs, in all studied areas. The isotopic methods yield the transit time in order of years. This relatively long mean transit time is typical even for Moravian Karst with well-developed endo- and exokarst. It is caused by slow diffuse flow in soil, unsaturated and saturated zone, generally in whole environment around karst conduits. On the other hand, the mean transit time in conduits is shorter in orders of magnitude. It varies from several hours up to 40 days based on tracer test in all karst areas.

INTRODUCTION

This study is focused on transit time of water in different parts of karst environment. Transit time in conduits was studied by tracer tests, transit time in saturated and unsaturated zone by means of environmental isotopes (^{18}O, tritium).

In the Czech Republic there are many rather small karst occurrences. They are surrounded by extensive areas occupied by non-karstic rocks (contact karst). Extent of particular areas varies from less than 1 km^2 up to 140 km^2. These areas differ in geology (lithology, tectonics, intensity of metamorphism) and intensity of karst development as well. This variety of environments enables to compare the transit time in different types of karst

Eleven karst springs were selected to be studied by isotopic methods (^{18}O, ^{3}H) and tracer tests (Fig.1). Springs are located in different geological settings: Two springs discharge from Cretaceous limestone and marlstone (Miskovice and Turnov Karst). Four springs drain Paleozoic rocks (Moravian and Bohemian Karst). Five springs are situated in metamorphosed carbonates (crystalline limestones). There are significant differences in different degree of karst development in catchments of particular springs. Moravian and Turnov karsts represent areas with well-developed underground net of extremely permeable conduits. Nearly all streams entering the Moravian Karst sink to underground. On the other hand, there are nearly no sinks in the area of the Bohemian Karst, conduits are only sparse and mostly bathyfreatic.

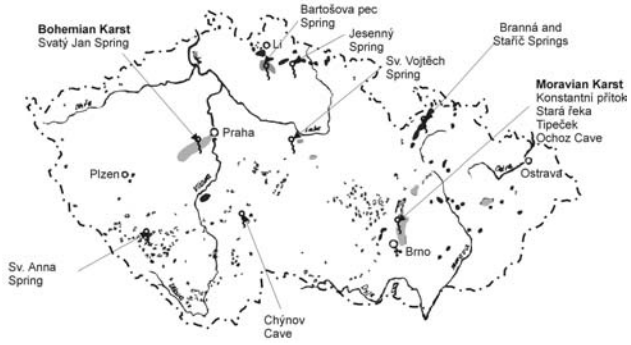

Figure 1. Karst areas in the Czech Republic (black - crystalline limestones; gray - Paleozoic and Cretaceous sedimentary limestones.

METHOD

In years 2001 - 2002 eleven selected springs were sampled to determine ^{18}O and tritium. To assess the transit time of water in unsaturated zone, three distinct drip waters were sampled on ^{18}O in the Ochoz Cave, Moravian Karst. Between 8 and 14 samples of ^{18}O were collected and analysed from each object. Mean transit time was obtained by FLOW model (Maloszewski and Zuber 1996). The variation of ^{18}O in monthly precipitation was fitted with signal in spring water. Dispersion and exponential models produced the best fit.

Several tracer tests in spring catchments were carried out to determine the velocity of flow in karst conduits. Archive tracer test from these karst areas have been studied as well. Tracer test were analyzed by Qtracer2 program (EPA 1999). As a result, there are 5 karst springs, where both, transit time based on isotopic methods and tracer tests could be compared (Tab.1).

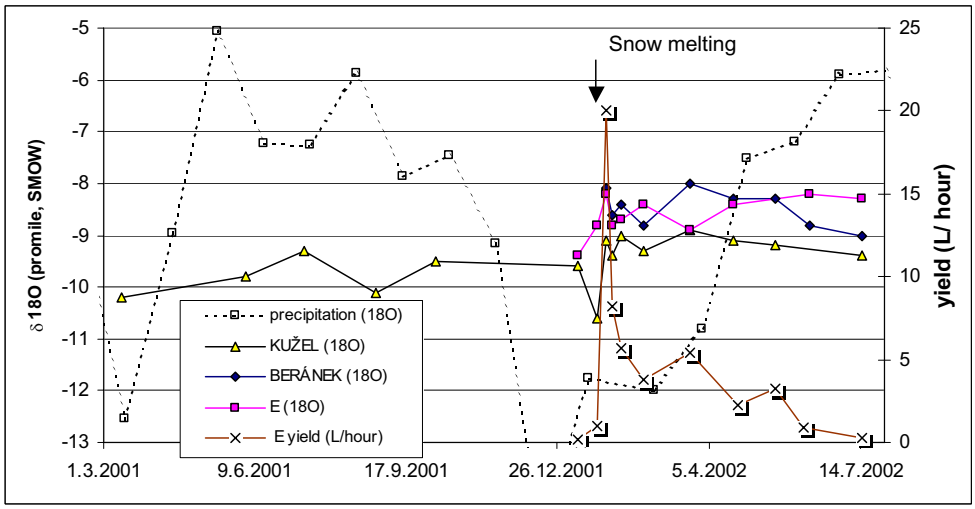

Figure 2. Variation of ^{18}O content in three dripp waters in the Ochoz Cave and weighted monthly ^{18}O content in precipitations. Yield of dripp place E (only 2002). Note that variation of ^{18}O in dripp water is much lower compared to precipitation

RESULTS

Tritium content varies between 14 - 22 TU in studied springs. It shows that water recharged after 1950 predominates in all springs.

Results of FLOW model (^{18}O) show that the mean transit time exceeds 1 year in all the springs. The only exception is the Tipeček Spring in the Moravian Karst (4 months). Commonly, predominant component seems to have stable ^{18}O content, which means the transit time exceeding 4 years. This relatively long mean transit time is typical even for the Moravian Karst with well-developed endo- and exokarst. Yet, these results are preliminary as this year samples have not been analysed. Even in 60 m thick unsaturated zone, the transit time of water exceeds 6 months (Fig. 2).

On the other hand, the mean transit time in conduits vary from several hours up to 40 days based on results of tracer test.

Hence difference in orders of magnitude exists if we compare the transit time obtained from tracer tests with transit time obtained from isotopes on the same springs (Tab.1) This is similar in all studied areas, irrespectively of geology and intensity of karst development. It seems that this feature is typical for karst areas. Authors believe, that this "discrepancy" is explainable by different behaviour of both type of tracers:

Concerning tracer tests, tracer is injected directly into sinks drained by conduits. Transit time obtained from tracer tests therefore shows the transit time in conduits.

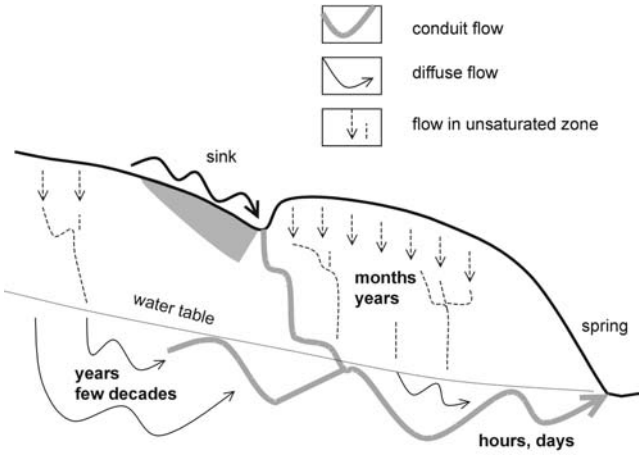

Figure 3. Sketch of karst environment with typical transit times of water based on tracer test and isotopic methods (Czech Republic)

On the other hand, environmental isotopes infiltrate predominantly by diffuse recharge through soil and unsaturated zone. On studied springs concentrated recharge through sinks is negligible (mostly less than 10% of the whole recharge). Hence, environmental isotopes show the transit time in less permeable parts of unsaturated and saturated zone.

Transit time in karst environments

Three different environments basically exist in karst areas (Fig. 3):

1) Karst conduits occupying only negligible volume of the whole karst environment (<0.5 %), nevertheless draining over 95% of all the discharge from karst areas (Wortington in Klimchouk *et al*. 2000).. As a result of very low volume and large intensity of flow the transit time in conduits results in orders of hours or days.

2) Remaining environment, which consists of fractures, fissures and voids. Here, as a result of relatively large volume and very low intensity of flow the transit time is in orders of years and first decades.

3) Unsaturated zone. As a result of relatively large volume in soil, subsoil and epikarst and very low intensity of flow the transit time is in orders of several months (Moravian Karst) but also years (Yonge *at al.* 1985).

ACKNOWLEDGEMENT

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REFERENCES

EPA (1999) The QTRACER program for Tracer Breakthrough Curve Analysis for Karst and Fractured-rock karst aquifers. - U.S. Environmental protection agency hypertext multimedia publication in the Internet at http://www.epa.gov/NCEA/pdfs/qtracer/qtracer.pdf

Klimchouk A B,. Ford D C, Palmer A N, Dreybrodt W (2000) Speleogenesis, Evolution of Karst Aquifers. NSS, Huntsville, USA, pp 521

Maloszewski P, Zuber A (1996) Lumped parameter models for interpretation of environmental tracer data, in: Manual on mathematical models in isotope hydrology. IAEA-TECDOC-910:9-59.-International Atomic Energy Agency. Wien

Yonge C J, Ford D C, Gray J, Schwarcz H P (1985) Stable isotope studies of cave seepage water Chemi Geol 58: 97-105

area	spring	mean transit time (tracer tests)	mean transit time (isotopic methods)	geology and tectonics	exokarst development
Bohemian Karst	Sv. Jan	30 hours [1)]	30% 1 month, 70% 22 years [1)]	Devonian limestones (folded)	at places only
Chýnov Karst	Rutice Chýnov Cave	cca 15 days	60% 14 months 40% over 4 years	highly metamorphosed carbonates	missing
Turnov Karst	Bartošova pec	16; 50; 110 hours	20% 1 month 80% over 4 years	Cretaceous marlstones (fractured)	developed
Miskovice Karst	Sv. Vojtěch	7 hours	10% 1 months 90% over 4 years	Cretaceous limestones (fractured)	at places only
Moravian Karst	Stará řeka	less than 100 hours	18 months	Devonian limestones (folded)	well developed

Table 1. Comparison of transit time determined by means of tracer tests and isotopic methods. [1)] Kadlecová et al (this volume)

New approach to using GIS in groundwater runoff assessment: the Krušné Mts., Czech Republic

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A b s t r a c t : One of the objectives of the EC LOWRGREP project was assessing groundwater runoff in the Krušné hory Mts. and in the Šumava Mts. within the Czech territory. Methodology for groundwater runoff assessment suggested by Krásný and Kněžek (1977), that was based on geomorphologic characteristics of the terrain and regionally prevailing transmissivity and recommended especially for mountainous hard-rock regions, has been modified to make full use of the Geographic Information System (GIS) advantages. Results obtained in this way from the Krušné hory Mts. are presented and compared with values of groundwater runoff determined by two other, entirely independent methods using a) precipitation/runoff Sacramento SAC-SMA model and b) the Kille's method. In accordance with the previous data (Krásný *et al.* 1981, 1982) the results from the test region showed high values of groundwater runoff up to 10 L/s/km^2 or even more, verified independently by all the used methods.

INTRODUCTION

Water managers often consider the hard-rock areas unproductive. That's true in most cases as far as the prevailing transmissivity is concerned as it is relatively low in general. On the other hand, groundwater runoff in mountainous areas, due to suitable climatic conditions (mostly high precipitation and low evapotraspiration) and by a steep morphology supporting an intensive groundwater flow in the near-surface hard-rock aquifer, used to be surprisingly high (Krásný *et al.* 1981, 1982, Krásný 1998). Methodology originally suggested by Krásný and Kněžek (1977), based on geomorphologic characteristics of the terrain and regionally prevailing transmissivity and recommended especially for mountainous hard-rock regions, has been modified to make full use of the Geographic Information System (GIS) advantages.

Within the EC 5th Framework Programme of the LOWRGREP project the new method based on the GIS application has been implemented and tested. Results from the Krušné hory Mts. are presented and compared with groundwater runoff values assessed by two other, entirely independent methods: from precipitation/runoff Sacramento SAC-SMA model (Burnash 1995) and an assessment having used the Kille's method (Kille 1970).

Figure 1. Situation of the test region

METHODOLOGY AND DATA PROCESSING

The fundamental idea of data processing using GIS procedures is based on the method of groundwater runoff assessment in crystalline complexes suggested by Krásný and Kněžek (1977). The method was based on groundwater throughflow estimation till that time applied, as one of the procedures to assess groundwater resources, only in hydrogeologic basins. The method of Krásný and Kněžek principally differs from other methods for groundwater runoff assessment that have been based on hydrologic approaches as precipitation-runoff modelling or separation of groundwater and surface water components from total runoff. Three main assumptions reflecting hydrogeologic conditions and groundwater flow within mountainous areas formed by crystalline rocks (and by rocks of low permeability in general) were accepted when the method have been applied:

The depth to groundwater level is typically up to a few metres below the ground surface and conformably copies the morphology and slopes of the terrain.

The groundwater flow is mostly confined to the shallow near-surface weathered and fractured zone the thickness of which reaches up some tens of meters: This correlates with the depth of most of water wells drilled in this hydrogeologic environment. Therefore, transmissivity values determined by these wells can be considered representative when assessing groundwater runoff.

Water courses represent the zones of groundwater discharge draining most of groundwater of the respective areas.

Krásný-Kněžek (1977) in fact modified the Darcy's law that in its simple form can be expressed as follows:

$$Q = k \cdot I \cdot F. \text{ or } Q = T \cdot I \cdot w \qquad (1)$$

where Q = groundwater flow through a vertical section of an area F or of a width w; k, T = the coefficients of hydraulic conductivity or transmissivity, resp., and I = hydraulic gradient.

In accordance with the above-mentioned assumptions hydraulic gradient of groundwater level in hilly/mountainous regions was identified with an average terrain gradient S determined in squares of the uniform size P (e.g. 25 km^2), covering the whole study area, from the total length of selected contour lines L in the sames areas P and the height interval between the used contour lines Z:

$$S = Z \cdot L / P \qquad (2)$$

The total amount of groundwater runoff in mountainous regions is discharged by a network of watercourses. Therefore, the density of this network D expressed as

$$D = W / P \qquad (3)$$

where W = the total length of all perennial watercourses in the area P (see equation 2). W substitutes the width of the groundwater throughflow section w in equation (1). As groundwater flows to surface streams from slopes following the both sides of valleys the amount of drained groundwater should be doubled compared with the equation (1). The final modified equation to assess groundwater runoff in hard-rock terrains Q is

$$Q = T \cdot I \cdot 2D \qquad (4)$$

.

Tabule 1. Estimation of baseflow by Kille method, Sacramento (SAC-Ma) model, Krásný, Kněžek (1977) and hydraulic model (Modflow) ***analyzed period 1968-1998 for Rolava***

model	Kille	SAC-SMA	Krásný, Kněžek (1977)				Modflow
average rainfall at the watershed [mm/year]	874	874	874	874	874	874	874
average rainfall at the watershed [L/s/km^2]	27.68	29.78	27.68	27.68	27.68	27.68	27.68
average flow from the watershed [L/s/km^2]	17.05	18.34	17.05	17.05	17.05	17.05	17.05
area P [km^2]	137.60	127.90	137.60	137.60	137.60	137.60	137.60
major river length L [km]	113.48		113.48	113.48	113.48	113.48	113.48
river density H=L/P [1/m]			8.25e-4	8.25e-4	8.25e-4	8.25e-4	
terrain slope S [-]			0.12	0.12	0.12	0.12	
transmissivity or specific yield P [%]			50	50	50	60	55

specific capacity or transmisivity set region of origin	Krušné Mts. Rolava catchment						
specific capacity q [m3/s/m] - representative set				**6.00e-5**	**5.00e-5**	**3.50e-5**	
transmissivity by Geofond T [m2/s] - representative set			**7.00e-5**				4.00e-5
baseflow (Kille method) [L/s/km2]	**8.03**						
supplementary - seasonal baseflow (SAC-SMA) [l/s/km2]		**9.66**					
total baseflow (SAC-SMA) [L/s/km2]		**15.44**					
baseflow (Krásný, Kněžek) [L/s/km2]			**14.39**	**12.34**	**10.28**	**7.20**	
baseflow [L/s/km2]							**8.00**

Nowadays, most of the tedious and time-consuming work of the parameters calculation can be replaced by modern procedures based on GIS techniques as using digital models of a terrain in determining gradients of terrain slopes or lengths of watercourses

RESULTS AND DISCUSSION

Comparison of results of groundwater runoff obtained by different approaches in the tested region of the Krušné hory Mts. can be seen in Tab.1. Values assessed by GIS procedures showed relatively high values of the specific groundwater runoff expressed in L/s/km^2. Nevertheless, high values round 10 L/s/km^2 or even more are in hilly/mountainous regions of the Bohemian Massif common and have been proved by various studies (e.g. Ferda *et al*. 1971, Krásný *et al*. 1981, 1982).

It is logical and can be also seen from Tab.1 (its lower part) that rock transmissivity (specific capacity) significantly affects assessment of groundwater runoff. Due to limits in technical possibilities and that time existing knowledge of transmissivity spatial distribution, Krásný and Kněžek (1977) used regionally valid prevailing transmissivity resulting from statistical treatment of pumping-test data in respective catchments or accepted data based on analogy.

Using GIS procedures, the calculations can be carried out alternatively using different transmissivity values in different areas. Results of recent studies proved important differences in spatial transmissivity distribution, due to occurrences of inhomogeneity elements of different scale (Krásný 1998, 1999). For groundwater runoff assessment especially differences in prevailing transmissivity between groundwater recharge areas (terrain elevations and slopes) and discharge areas (bottoms of valleys) are of importance. It was found that in hard-rock regions prevailing transmissivity typically reach 2.5-4 times higher values in the discharge than in recharge areas. Therefore, even hard-rock hydrogeologic environment cannot be considered as a regionally homogeneous one but rather as a complex system of belts of regional higher prevailing permeability (transmissivity) following valleys. This might be a way of improving implementation of conceptual and consequently numerical models of groundwater runoff (and thus natural groundwater resources) assessment.

In addition, GIS procedures enable a flexible choice of all other parameters to be used as variable morphometric characteristics (slope of terrain, density of watercourses) even though these do not seem to be as important as the transmissivity values where the relatively small differences might influence considerably final results (comp. Tab.1). Calibration of models will be of help also in inverse solutions of reliable transmissivity values in mountainous hard-rock environment. This will be the principal advantage of using GIS methodologies compared with the original and relatively simple approach of Krásný and Kněžek (1977).

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REFERENCES

Burnash JCR (1995) The NWS River forecast system – catchment modelling. In: Singh VP (ed) Computer models of watershed hydrology. Water Res Publ Highlands Ranch, Colorado:311-366

Ferda J, Hladný J, Bubeníčková L, Pešek J (1971) Run-off regime and water chemistry in the Otava catchment with regards of the peat bogs (in Czech). Annual report of the Hydrometeor. Institute 17:22-26. Prague

Kille K (1970) Das Verfahren MoMNQ, ein Beitrag zur Berechnung der mittleren langjährigen Grundwasserneubildung mit Hilfe der monatlichen Niederigwasserabflüsse. Z Deutsch Geol Gessell.:89 – 95

Krásný J (1998) Groundwater discharge zones: sensitive areas of surface-water - groundwater interaction. In: Van Brahana J, Eckstein, Ongley LK, Schneider R, Moore JE (eds) Gambling with groundwater. Proc. joint meeting 28 IAH Congress and Annual meeting of AIH, Las Vegas:111-116

Krásný J (1999) Hard-rock hydrogeology in the Czech Republic. Hydrogéologie, 2:25-38 Éditions BRGM. Orléans

Krásný J, Kněžek M (1977) Regional estimate of ground-water run-off from fissured rocks on using transmissivity coefficient and geomorphological characteristics. Journal of Hydrol Sciences 4(2):149-158. Warsawa

Krásný J (ed), Kněžek M, Šubová A, Daňková H, Matuška M, Hanzel V (1981) Map of groundwater runoff of Czechoslovakia in 1.1,000,000. Czech Hydrometeor. Institute Prague

Krásný J, Kněžek M, Šubová A, Daňková H, Matuška M, Hanzel V (1982) Groundwater run-off in the territory of Czechoslovakia (in Czech, English summary). Czech Hydrometeor. Institute Prague, 50 pp

GIS based assessment of groundwater recharge in the fractured rocks of Namaqualand, South Africa

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A b s t r a c t : For the improved assessment and management of groundwater resources in a semi-arid environment, it is essential that accurate groundwater recharge estimations be obtained. One of the challenges of determining groundwater recharge in this semi-arid area is that groundwater flow occurs principally in fractures and fissures.
The recharge assessment was carried out using a geographical information system (GIS). The approach taken was based on a rating and weighting methodology. The data sets taken into account for the determination of effective groundwater recharge included: lineaments; land cover; soil type; soil thickness; soil texture; slope; depth to groundwater; and lithology.
Once the relative groundwater recharge percentage map was produced, the results were then applied to annual precipitation data. A number of assumptions were made during the analysis, however, due to the processing being GIS based, the improvement of results with revised data sets is quickly carried out.

INTRODUCTION

The study area is situated in Namaqualand, South Africa, and includes quaternary surface water catchments F30, F40 and F50 (Fig.1). For the improved assessment and management of groundwater resources in a semi-arid environment, it is essential that accurate groundwater recharge estimations be carried out. One of the challenges of determining groundwater recharge in this semi-arid area is that groundwater flow occurs principally in fractures and fissures and is not uniformly disturbed across the region. The annual average rainfall varies from 44 mm in the coastal area to 480 mm in the Kamies Mountains. Groundwater is mainly abstracted from alluvial and crystalline basement aquifers. The aquifers are sole sources for most of the towns in the area. The fractured aquifers are generally characterised by low storage capacity and high transmissivities.

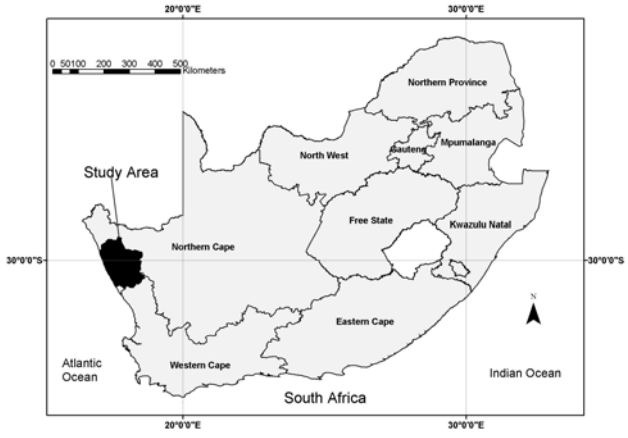

Figure 1. Location of the study area, within Namaqualand

In order for the assessment to be carried out, an extensive international literature survey was carried out. This survey assisted in determining a methodology for carrying out a spatially distributed recharge assessment. Following on from this survey, it was necessary to pull many data sets together into one coincident spatial database. In addition new data sets were purchased to enhance the analysis process. Once all the data had been collated it was analysed and processed. The approach taken was based on a rating and weighting methodology and a number of limitations are present. These limitations have been identified and can be addressed in due course.

Once the qualitative relative groundwater recharge map was produced, it was hoped that it could be verified with actual recharge estimates obtained from borehole recharge analyses. However, individual borehole analyses have not yet been finalised and a range of values obtained from literature was used to calibrate the relative recharge map. The percentage recharge results were then applied to the annual precipitation data to obtain a volume of effective groundwater recharge.

A number of assumptions were made during the analysis and the ratings and weightings assigned were subjective. However, having processed the data and carried out the analysis in GIS, the changing of values and viewing of results is relatively quickly carried out. The possibility then exists of refining the input data sets and improving the recharge values.

METHODOLOGY

For this GIS based project to be carried out, it was essential to collate numerous data sets, including the Landsat TM image and a digital elevation model. The projection chosen for this purpose was the southern UTM zone 34 (WGS84 datum). UTM was chosen as all distances, directions, shapes and areas are reasonably accurate within 15^{o} of the central meridian. As this projection is conformal, shape and angles within any small area are essentially true. Extensive data reworking and re-projecting occurred to produce a coincident and valid spatial database. In addition, a number of data sets were purchased to enhance the analysis.

The broad approach taken for this groundwater recharge assessment project was to adopt a rating and weighting methodology. The input data sets and associated weightings (1-5) include: Lineaments + flow potential (confirmed by NDVI/SAVI) (5); Lineament density (2); Lineament intersections (2); Drainage density (3); Land cover (1); Soil type (clay content) (1); Soil thickness (1); Soil texture (% rock vs % soil) (1); Slope (degrees) (5); Depth to groundwater (1); Lithology (geology) (4); and total annual rainfall for 2000 (none). The range of values within each data set was then determined and a recharge probability ranging from 100% to 50% was assigned to the range of values.

All data processing was carried out using a raster-based approach. A cell size of 50 m was used for all gridded data sets. The processing was carried out using Arc/Info, ArcView, Spatial Analyst and Erdas.

The process followed for this project included a visual assessment of geological lineaments, mapped from the Landsat TM image (p176r081), acquired in December 1999. The lineaments were mapped at a scale of 1:250 000. Wherever possible a differentiation was made between different types of lineaments.

In an attempt to assess the groundwater flow potential of each lineament, a normalized difference vegetation index (NDVI) and a soil adjusted vegetation index (SAVI) was generated from the Landsat TM image. The SAVI was suggested by Kellgren *et al*. (2000) as a better method for this purpose, however for this particular scene the difference between the NDVI and the SAVI was minimal. Lineaments associated with higher NDVI values were assumed to be moister and to hold greater potential for the occurrence of groundwater flow. The lineaments were also visually assessed in terms of groundwater flow potential and in conjunction with the NDVI, a qualitative value of high, medium and low were assigned to the lineaments. For the high flow lineaments a buffer distance of 200 m was assigned and this zone given a 90% probability for recharge potential. The medium flow lineaments were buffered by 100 m and assigned a 70% recharge probability and the low flow potential lineaments buffered by 50 m and given a 50% recharge probability.

For assessing the amount of precipitation interception and evapotranspiration the national land cover data set was purchased and used. The land cover types are based on mapping carried out by the ARC and CSIR from 1:250 000 Landsat TM images.

Soil characteristics are also important in determining effective groundwater recharge. The only soil information available at a scale comparable to this study (i.e. 1:250 000) is the ISCW Land Type data set. The Land Types were mapped nationally at a scale of 1:250 000 and take into account terrain form, topography and micro-climate. Land Types were derived to assist in determining agricultural potential. Although actual soil types are not mapped, useful information associated with Land Types includes the percentage clay, soil thickness and texture within each Land Type.

The slope was calculated from the digital elevation model. The steeper the slope the greater the precipitation runoff and the smaller the groundwater infiltration.

The thickness of the unsaturated zone is considered a relevant factor in calculating recharge potential. The deeper the groundwater the more likely the adsorption of infiltrating surface moisture within the unsaturated zone and the more effective groundwater recharge is reduced.

The input data for the depth to groundwater level parameter needs to be carefully assessed before being used to generate groundwater level surfaces. An important issue is to determine whether the borehole water levels recorded are dynamic or static values. In addition, the fractured flow dominated nature of groundwater occurrence should be taken into account when generating a depth to water level contour map. In addition, input values also need to be assessed as to whether they are representing confined or unconfined aquifer conditions.

The final factor taken into account was geological lithology. The geological information was derived from the primary lithology map, produced by the Council for Geoscience at a scale of 1:1 000 000.

All the input coverages were converted to 50 m grids with the same area of extent. Each grid was then reclassified according to classification tables and then also weighted according to how significant the individual factor was considered to be in contributing to groundwater recharge potential. Once the weights had been applied to the grids they were then summed and the final grid sub-divided into 7 qualitative classes ranging from low to high relative recharge potential.

The next step was to obtain effective groundwater recharge values per borehole for the study area. This exercise is currently being carried out and once the values are obtained they will be used to calibrate the grid into a percentage effective groundwater recharge grid. However, in the meanwhile a range of values for groundwater recharge in Namaqualand was obtained from Murray (1996). Murray (1996) reports that values for aquifers in the Northern Cape, North West Cape and Botswana give recharge values that range from 0.7 % to 1.0% MAP. This range of values was applied to the qualitative groundwater recharge potential grid and then multiplied with the total precipitation map for the year 2000. The final grid represents the actual effective groundwater recharge map for the study area for the year 2000 in millimetres. This value can also be converted to a value of mm/annum/km^2 for groundwater management and abstraction purposes if need be.

RESULTS

A number of assumptions need to be made to arrive at a groundwater recharge potential map. The fracture flow dominated mechanisms complicate the determination of effective groundwater recharge, however by adopting a best-estimate approach a final answer of effective recharge can be produced. In addition to revealing actual recharge amounts the spatial variability of recharge across the study area is shown. The recharge map provides valuable information for groundwater resource management, although in a fracture flow dominated environment, recharge areas may occur significant distances away from the area of abstraction. It is also still necessary to verify the results obtained with recharge estimates calculated on borehole water level and chemistry data.

DISCUSSION

The results obtained do reflect the conceptual thinking on recharge occurrence within the area, however further refinement and calibration is required. The approach used does not adequately take into account the 3 dimensional fractured dominated flow occurrences and mechanisms of groundwater. However a first approximation was made and a methodology developed. It is essential to obtain a greater understanding of the structural and tectonic history of the area as well as the recharge estimates from individual borehole assessments, using the most appropriate methods. The advantage of a GIS approach is that parameters can easily be changed and the results rapidly viewed and assessed.

ACKNOWLEDGEMENTS

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REFERENCES

Kellgren N, Sander P, Blomquist-Lilja N, Groenewald J, Smit P, Smith L (2000) Remote Sensing Data for Effective Borehole Siting. Progress Report 3. Dept. of Geology, Chalmers University of Technology, Göteborg, Sweden

Murray R (1996). Guidelines for assessing single borehole yields in secondary aquifers. MSc thesis, Rhodes University, South Africa

Groundwater ages in fractured rock aquifers

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A b s t r a c t : In fractured rock aquifers, the distribution of groundwater ages will depend on fracture and matrix properties. Simple analytical models are available for describing groundwater age profiles for one-dimensional flow through vertically-fractured aquifers. With the aid of numerical models, we investigate the effect of horizontal fractures on these age profiles. Using this same model, simulations of observed groundwater ages within the Clare Valley, South Australia, are used to constrain aquifer parameters.

INTRODUCTION

There have been many studies in which groundwater ages in porous media aquifers have been used to determine groundwater flow velocities. In fractured porous media, however, solute transport is characterised by rapid advection through the fractures, with diffusive exchange between solute in the fractures and that in the relatively immobile water in the matrix. The result is apparent groundwater ages obtained with environmental tracers that do not reflect the hydraulic age of the water. Despite this, groundwater ages in fractured rock aquifers are usually interpreted using piston flow models, a practice that can result in serious errors in the estimated flow velocities. In this paper we describe how groundwater ages in fractured rock aquifers can be used to obtain information on aquifer properties and groundwater flow velocities through fractures, using models that represent fracture flow and matrix diffusion processes. In the first section of the paper, we consider groundwater age distributions that arise due to one-dimensional flow through vertical fractures. Next, we consider how these profiles are modified by two-dimensional flow, and by the presence of horizontal fractures. Finally, we briefly describe the use of these models to simulate field data from the Clare Valley, South Australia.

ONE-DIMENSIONAL FLOW THROUGH VERTICAL FRACTURES

In vertically-fractured media, analytical and numerical models have been used to relate apparent groundwater ages determined using environmental tracers to aquifer parameters. For example, Sudicky and Frind (1982) presented an analytical solution for the transport of a constant source, radioactive tracer through a system of planar, parallel vertical fractures. Assuming constant input of ^{14}C, and negligible dispersion, the apparent ^{14}C ages within fractures can be expressed

$$\frac{t_a}{z} = V_w^{-1}\left[1+\frac{\theta_m^{½}D^{½}}{b\lambda^{½}}\tanh\left(B\theta_m^{½}D^{-½}\lambda^{½}\right)\right] \qquad (1)$$

where t_a is the apparent groundwater age, z is depth, V_w is the vertical water velocity within the fractures, θ_m is the matrix porosity, D is the ^{14}C diffusion coefficient within the matrix, λ is the radioactive decay constant for ^{14}C, $2b$ is the fracture aperture and $2B$ is the fracture spacing. (The diffusion coefficient within the matrix is given by $D = D_0\theta_m\tau$, where D_0 is the free solution diffusion coefficient and τ is the tortuosity.) The vertical water velocity within the fractures is related to the aquifer recharge rate (R) by $V_w b = RB$. Cook and Simmons (2000) suggested that (1) could also be used to approximate chloroflourocarbon ages within fractures, if the CFC input function could be approximated by an exponential growth curve (ae^{-kt}). In this case, the decay constant, λ, is replaced by the exponential growth rate, k.

Cook and Simmons (2000) also argued that an analytical solution for the transport of a short 'top-hat' pulse of solute through a system of planar, parallel fractures could be used to approximate the transport of ^3H and ^{36}Cl through vertical fractures. Where the fracture spacing is large (no interaction between adjacent fractures) and dispersion within fractures is negligible, the concentration within the fracture as a function of depth can be approximated by

$$\frac{c(x,t)}{c_0} = \frac{TD^{½}\theta_m z}{2bV_w\pi^{½}t^{3/2}}\exp\left[\frac{-D\theta_m^2 z^2}{4tb^2V_w^2}\right] \qquad (2)$$

where c_0 is the concentration of tracer during the pulse input after correction for radioactive decay (zero at other times), T is the length of the pulse and t is the time which has elapsed since the commencement of the pulse (Lever and Bradbury 1985). It is relatively straightforward to show that the maximum ^3H concentration will occur at a depth given by

$$z_{\max} = \frac{RB}{\theta}\sqrt{\frac{2t}{D}} \qquad (3)$$

These analytical solutions assume simple patterns of tracer input. However, while they are useful for understanding groundwater age patterns in the subsurface, actual tracer inputs do not exactly match those assumed by the analytical models. Numerical simulations of ^{14}C, CFC-12 and ^3H transport through identical, planar, parallel vertical fractures in an impermeable matrix have been presented by Cook and Simmons (2000) using measured atmospheric input concentrations for these tracers. Cook and Robinson (2002) carried out simulations of ^3H and ^{36}Cl profiles in vertically-fractured aquifers, and investigated how these profiles varied with the fracture aperture and fracture spacing, matrix porosity, matrix diffusion coefficient and aquifer recharge rate.

TWO-DIMENSIONAL FLOW THROUGH HORIZONTAL AND VERTICAL FRACTURES

Where large horizontal fractures occur within the profile, these can intercept the vertical moving groundwater and divert it laterally. We have examined the influence of horizontal fractures on groundwater ages using the numerical model FRAC3DVS (Therrien and Sudicky 1996). The model dimensions are 100 m × 100 m × 1 m. In all cases, a single vertical fracture with aperture 100 μm ran the length of the model, with no flow boundaries located 0.5 m either side of this fracture, to simulate flow through identical parallel fractures with a spacing of 1 m. The matrix hydraulic conductivity was set to be very low, to simulate flow through fractures only, but with diffusion into the matrix. The matrix porosity was set to $\theta_m = 0.02$, and tortuosity was $\tau = 0.03$. A specified flux of 15 mm/yr on the upper boundary was used to simulate aquifer recharge.

Initially, a simulation was carried out to simulate vertical flow only, by using no flow boundary conditions on all sides and a constant head boundary condition on the lower boundary. The resulting profiles within the vertical fracture and within the

matrix 0.5 m from the fracture are shown as the solid line in Fig.1. For all the remaining simulations, the lower boundary condition was no flow, and the right-hand boundary was constant head, to simulate a two-dimensional flow field.

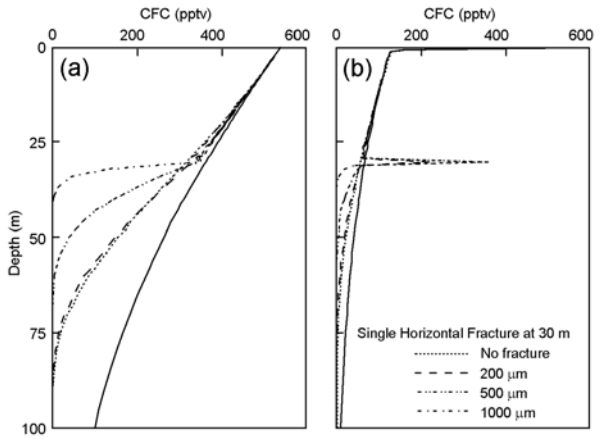

Figure 1. Simulations of CFC-12 concentrations (a) in vertical fracture, and (b) midway between vertical fractures, for a two-dimensional flow field comprising identical planar parallel vertical fractures, with and without horizontal fractures at 30 m depth. The solid line depicts the CFC-12 profile for a one-dimensional flow field

Even in the absence of the horizontal fracture, CFC-12 concentrations at all depths are somewhat less than in the vertical flow simulation. This results from the curvature of the flow lines in a two-dimensional flow field. (In porous media, groundwater ages increase linearly with depth in a vertical flow field, and exponentially with depth in a two-dimensional flow field.) Where the horizontal fracture aperture is 200 μm, it has minimal effect on CFC-12 concentrations within the vertical fracture. Increasing the fracture aperture has two noticeable effects. Firstly, concentrations above the fracture increase. This occurs because the fracture acts as a drain, and water is drawn down vertically towards it. It decreases the horizontal component of the groundwater flow at shallow depths. Increasing the horizontal fracture aperture also decreases concentrations below the fracture, as the vertical flow velocity is reduced by water draining laterally through the fracture.

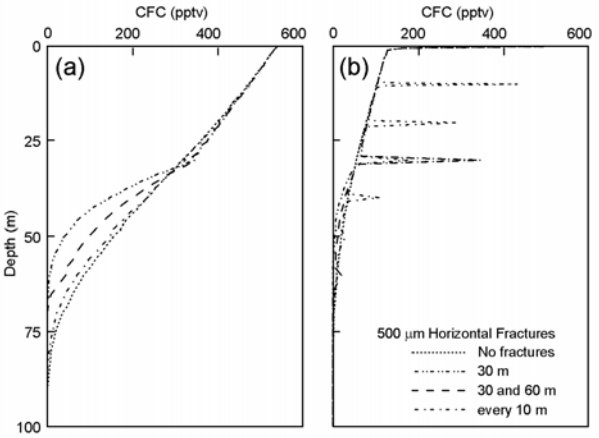

Figure 2. Simulations of CFC-12 concentrations (a) in vertical fracture, and (b) midway between vertical fractures, for a two-dimensional flow field comprising identical planar parallel vertical fractures, with different numbers of horizontal 500 μm fractures

Fig.2 shows the effect of increasing the number of horizontal fractures. In all these simulations, the horizontal fracture aperture is 500 μm. The addition of an additional horizontal fracture at 60 m depth causes an increase in concentration at depth, as water is drawn deeper into the aquifer to flow through these deeper flow paths. As the number of horizontal fractures increases further, the influence of each fracture decreases, so that ultimately the concentration profile approaches that for the single vertical fracture, with no horizontal fractures.

FIELD EXAMPLE

Vertical profiles of ^{14}C, ^{36}Cl, ^{3}H and CFC-12 have been obtained from piezometer nests constructed in fractured metamorphic rocks in the Clare Valley, South Australia (Cook and Simmons 2000; Cook and Robinson 2002). We have carried out numerical simulations to reproduce the observed profiles, based on flow through a series of parallel vertical fractures, intersected by a single, large aperture horizontal fracture. The horizontal fracture reproduces the large increase in groundwater age that is observed to occur between 30 and 40 m depth within the aquifer. The numerical simulations provide a reasonable fit to concentrations of all tracers, using reasonable values of aquifer parameters, and an aquifer recharge rate of 70 mm/yr.

CONCLUSIONS

Numerical simulations have suggested that it may be reasonable to use of one-dimensional models of flow and transport through vertical fractures to represent flow through aquifers containing both horizontal and vertical fractures. Tracer concentrations (and hence apparent groundwater ages) at a given depth within fractured rock aquifers will be a function of the spacing and aperture of the vertical fractures, the matrix porosity and effective diffusion coefficient and the aquifer recharge rate. The presence of large numbers of horizontal fractures will not cause flow to depart significantly from the one-dimensional approximation. Where a smaller number of horizontal fractures are present, then these can act as drains, and large increases in groundwater age can occur below the fractures.

REFERENCES

Cook PG, Simmons CT (2000) Using environmental tracers to constrain flow parameters in fractured rock aquifers; Clare Valley, South Australia. In: Faybishenko B, Witherspoon PA, Benson SM (eds) Dynamics of Fluids in Fractured Rock. Geophysical Monograph, 122 American Geophysical Union, pp 337-347

Cook PG, Robinson NI (2002) Estimating groundwater recharge in fractured rock from environmental 3H and 36Cl; Clare Valley, South Australia. Water Resources Research, 38(8):10.1029/2001WR000772

Lever DA, Bradbury MH (1985) Rock-matrix diffusion and its implications for radionuclide migration. Mineralogical Magazine 49:245-254

Sudicky EA, Frind EO (1982) Contaminant transport in fractured porous media: analytical solutions for a system of parallel fractures. Water Resources Research 18(6):1634-1642

Therrien R, Sudicky EA (1996) Three-dimensional analysis of variably-saturated flow and solute transport in discretely-fractured porous media. Journal of Contaminant Hydrology 23(1):1-4

Quantitative limits for groundwater exploitation under natural conditions in southwest Ghana

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A b s t r a c t : Groundwater is the most cost-effective option of safe water supply to rural communities in Ghana. To determine the groundwater resources potential and the threshold of groundwater development, studies on recharge to the weathered aquifers and statistical evaluations of specific capacity in the Pra river catchment in SW Ghana have been undertaken. The SAC-SMA conceptual hydrological modelling system was used for the recharge estimates. With recharge rate of 50 mm/yr, the natural groundwater resource is estimated to support a maximum withdrawal of 12 L/s for a 10 hour per day pumping. Except in zones of higher permeability where the rocks permit the abstraction of larger quantities of groundwater, recharge will not be a limiting factor in groundwater resources development from storage in the basin. The groundwater resources potential of 1.6 L/s/km^2 could be considered the threshold of groundwater exploitation for similar river basins in SW Ghana.

INTRODUCTION

The economic importance of groundwater in Ghana can be hardly emphasised too strongly, since groundwater remains the most reliable alternative source of water supply for the numerous scattered rural communities in Ghana. About 33% of the population is supplied by groundwater. Hard consolidated rocks however, underlie the greater part (about 80%) of the country making it difficult to develop large concentrated supplies of groundwater. There is therefore the need to ascertain the groundwater resource potential to find out if the increasing withdrawal is sustainable.

To determine the threshold of groundwater abstraction, and verify the methodological approach of assessing natural groundwater resources of hard rocks in a tropical setting, studies on well productivity and direct natural recharge to the shallow aquifers in a major river basin (Pra River) in SW Ghana have been carried out. The limiting effects of either permeability of rocks or replenishment of aquifers under natural conditions on groundwater development are also assessed.

The Pra river basin covers an area of about 22,836 km^2. The region is warm and moist throughout most of the year, and the vegetation is of moist semi-deciduous forest type. The mean annual temperature is 27 ^{0}C and the annual rainfall varies between 1170–1490 mm. The mean annual runoff ranges from 51 to 93 m^3/s, representing only about 6-9% of rainfall. Birimian rocks (phyllite, schist and tuff) and associated granitoid intrusives, as well as Tarkwaian rocks (quartzite, shale and conglomerate) of Precambrian age underlie the basin.

The available hydro-meteorological data used for the analysis and simulation consisted of daily records covering a period of six years (1987-1992).

METHODOLOGY

The Sacramento soil moisture-accounting (SAC-SMA) hydrological modelling system, developed and implemented by Burnash *et al.* (1973), was used to assess the natural groundwater resources within the basin. This involved the determination of the proportions of major components of the hydrologic budget by the simulation of rainfall–runoff processes. The primary elements involved were thus the catchment runoff and station precipitation, evapotranspiration and basin characteristics, and base flow analysis. Evaporation rates as inputs were estimated from meteorological variables, using long-term mean values. The primary base flow characteristics were generally estimated from the daily discharges when the flow rates remained almost constant for an extended period. During the simulation more emphasis was thus laid on low-flows. From the model output, recharge rates, as well as groundwater resources formation within the basin were estimated.

Statistical approach was adopted to estimate the potential for groundwater abstraction. Because it accounts for the loss in head that is associated with pumping, specific capacity is preferred to yield as a measure of well productivity (Knopman 1990). It also provides initial approximations to water abstraction possibilities in the hydrogeologic environment (Krásný 1993). The specific capacity of each well was computed and the sustainable yield was multiplied by an available drawdown of 5m.

MODEL OUTPUT AND GROUNDWATER STORAGE

Tab.1 presents the proportions of the various runoff components and fig.1 compares the observed and simulated discharges. The potential base flows constituted 90% of total runoff, with the long-term component (primary base flow) averaging about 50%.

Table 1. Proportions of runoff components in Pra river basin in SW Ghana (modified after Darko 2002)

Year	Simulated runoff components [%]					
	PRM	SUP	IMP	DIR	SUR	INT
1987	49.49	38.21	7.78	4.48	-	0.02
1988	53.15	36.47	6.70	3.62	-	0.04
1989	50.62	37.72	7.52	4.14	-	0.01
1990	52.52	33.63	8.66	2.19	-	0.01
1991	48.44	39.24	8.25	4.09	-	-
1992	54.83	35.45	7.41	2.25	-	0.01
Mean	51.51	36.79	7.72	3.46	-	0.02

Explanation: PRM=primary base flow; SUP=supplementary base flow; IMP and DIR=direct runoff from permanent and temporary impervious areas respectively; SUR=surface runoff when rainfall occurs faster than percolation and interflow can take; INT=interflow

Groundwater recharge was estimated by considering the measured discharge of groundwater across the boundary of the basin to be equal to the net recharge inside the catchment. Over periods of equivalent storage, recharge to groundwater is thus given by the long-term component of base flow from the hydrograph.

The results indicate that recharge will not be a limiting factor in groundwater resources development from storage in the Pra basin. Recharge would be sufficient to sustain the threshold yield of 5 L/s. This will be the case for basins in SW Ghana, which are represented by similar rocks that underlie the Pra river catchment. In more permeable zones however, the recharge area could

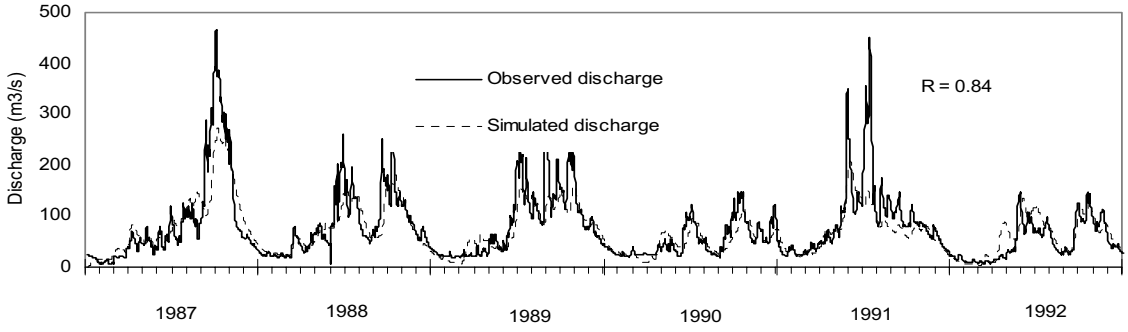

Figure 1. Observed and simulated discharges in Pra river basin in SW Ghana

The recharge rate mounted to an annual average of 50 mm. This represented 4% of mean annual rainfall of 1300 mm, giving natural groundwater resources potential of 1.6 L/s/km^2. Tab.2 gives the recharge variations for respective years.

Although the dangers of generalisations in hard rocks are obvious, in areas of shallow aquifers where the overburden forms the main groundwater reservoir, climatic and meteorological factors could mask geological conditions. Permanent components of base flows could represent recharge to the near-surface weathered and fractured rock aquifers in the basin.

Table 2. Results of recharge-runoff simulation for shallow aquifers in Pra river basin in SW Ghana

Year	Rainfall (mm)	Recharge (mm)	Recharge (% of rainfall)	Groundwater resources (L/s/km^2)
1987	1492.6	61.5	4.1	1.9
1988	1288.5	57.9	4.5	1.8
1989	1374.1	53.9	3.9	1.7
1990	1165.7	39.4	3.4	1.2
1991	1378.5	49.3	3.6	1.6
1992	1179.9	44.0	3.7	1.4
Mean	1313.2	51.0	3.9	1.6

THRESHOLD OF GROUNDWATER ABSTRACTION

The statistical evaluations of specific capacity gave an estimated sustainable yield of 0.8 L/s. For rural water supply, the average demand for a hand-pump will be 10,500 m^3/yr, over a 10 hour per day pumping, 365 day per year. If it is assumed that the yield is totally dependent on precipitation recharge, then an area of 0.2 km^2 will be required for its sustenance at the recharge rate of 50 mm/yr. This is equivalent to a recharge radius of only about 260 m around the borehole. Based on equivalent conditions and average aquifer characteristics for basement rocks, the cone of depression due to pumping would extend to at least 1000m around the borehole (Houston 1988). Taking the minimum reach of the depression cone as the first zone of environmental protection around the borehole for recharge, the natural groundwater resources in the basin is estimated to support a maximum withdrawal of 12 L/s for a 10 hour per day pumping. This is equivalent to 5 L/s for continuous pumping.

extend beyond the assumed 1000 m around the well and different abstraction scenarios will have to be simulated to arrive at the maximum possible withdrawal that will not mine the available groundwater in storage.

CONCLUSION

The potential base flow components (primary and supplementary base flows) constituted approximately 90% of total runoff, with the long-term component (primary base flow) representing an average of 50%. The mean annual recharge rate was approximately 50 mm. This represented about 4% of mean annual rainfall of 1300 mm, giving natural groundwater resources potential of 1.6 L/s/km^2. On temporal basis, the analysis showed that recharge correlated with rainfall (correlation coefficient = 0.8).

Permeability and aquifer replenishment could be the limiting factors on groundwater development in Ghana. In low permeable areas where wells can yield only limited quantities of water, results from the Pra river basin indicate that recharge would be sufficient to sustain a threshold yield of 5 L/s. This will be the case for most river basins in SW Ghana.

Longer data length will be required for comprehensive assessment of recharge. Since the necessary data for such evaluations are rarely available, it becomes imperative to apply a variety of techniques for cross checks and references.

REFERENCES

Burnash RJC, Ferral RL, McGuire RA (1973) A generalised stream flow simulation system: Conceptual modelling for digital computers. NWS and State of California Dept. of Water Res. Sacramento, 204 pp

Darko PK (2002) Estimation of natural direct groundwater recharge in SW Ghana using water balance simulations. J Hydrol.Hydromech 50(3):198-212

Houston J (1988) Rainfall-runoff-recharge relationships in the basement rocks of Zimbabwe. In: Lerner DN, Issar AS, Simmers I (eds) Groundwater recharge - a guide to understanding and estimating natural recharge. IAH 8:271-283

Knopman DS (1990) Factors related to the water-yielding potential of rocks in the Piedmont and Valley and Ridge provinces of Pennsylvania. US Geol Survey Water Resources Investigation Report 90, 4174 52 pp

Krásný J (1993) Classification of transmissivity magnitude and variation. Ground Water 31(2):230-236s

Determining the groundwater recharge mode of a fractured migmatitic aquifer at local scale in Benin, West Africa

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A b s t r a c t : The determination of the groundwater recharge mode of a fractured aquifer at local scale is one of the main goals of the ongoing work. The results, using methods like TDR, hydrochemical and isotope analysis of ground-, soil- and surface water as well as artificial tracer tests show clear deviations between the hydrogeochemical composition of ground- and soil water. The major groundwater inflow seems to take place in other recharge areas. Local recharge is limited by the structured unsaturated zone, with a low permeable lateritic strengthened zone. But due to windows within the lateritic aquitard recharge is possible in the wet season.

INTRODUCTION

In the framework of the BMBF (Federal Ministry of Education and Research) project "Global change of the water cycle", IMPETUS West Africa (integrated approach to the efficient management of scarce water resources in West Africa) focuses on water as a scarce resource. In this project thorough investigations of all aspects of the hydrological cycle are carried out within two river catchments in North and West Africa: the wadi Drâa in the southeast of Morocco and the river Ouémé in Benin. Within the hydrological cycle groundwater and groundwater recharge is of significant importance.

As one of the river catchments the Ouémé catchment in Benin (fig.1a, b) has been selected. Here, initially research on groundwater issues has been focused on local scale. Together with other disciplines investigations have been carried out in the Aguima catchment area (fig.1c), a 30 km² sized sub-catchment of the Térou, the main tributary of the Ouémé (Diekkrüger *et al*. 2002).

HYDROGEOLOGICAL SETTING

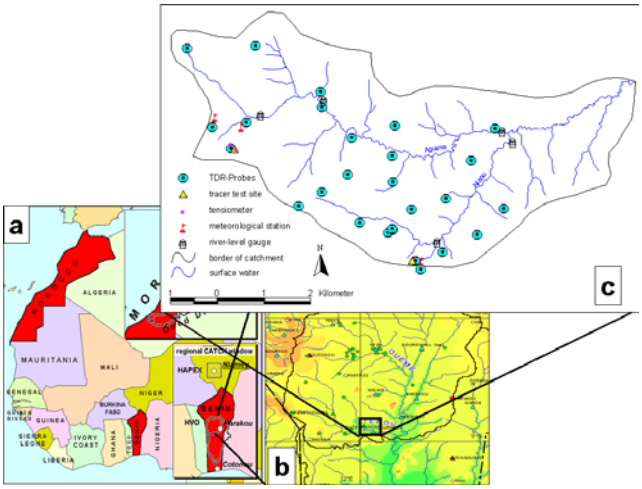

Figure 1. Working area in Benin (a). (b) shows the localisation of the 30 km^2 Aguima test site (c) in the upper catchment of the river Ouémé (14,000 km^2).

As part of the African Precambrian shield the aquifer in the area under investigation is build by granitoid and gneissic migmatites, characterised by a NW-SE striking (fractures) and NE-SW striking (faults, dikes) structural pattern (fig.2). Based on detailed evaluations of the geological setting of the Aguima catchment a conceptual hydrogeological model was elucidated (fig.3).

The vadose zone of the fractured aquifer consists of a saprolithic zone, followed by a lateritic decomposition and a soil zone.

SOIL MOISTURE

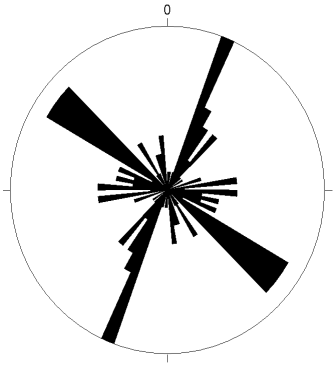

Figure 2. Rose-diagram of the structural pattern in the working area

In order to understand the local groundwater recharge processes a monitoring network has been established. Monitoring of the vadose system has been performed by 32 TDR measuring tubes representatively placed in the test site (fig.1c) in depths from 50 to 240 cm. Weekly measurement have been carried out with a mobile TDR tube access probe.

Based on these measurements the development of the soil water content in the unsaturated zone in respect to geology and lithology can be distinguished. Both a clear dependence of the soil moisture content on the substrate as well as a strong influence of low permeable horizons on the percolating water is evident (fig.4). The lateritic strengthened soil horizons act as aquitards (fig.4-B1/D1, B2/D2), where percolation of the infiltrating precipitation water is deviated and forms interflow (fig.3). However, a part of the percolate is able to pass the nearly impermeable lateritic horizons through preferential flow-paths and thus contribute to the groundwater recharge (fig.4-D2). Fluvisoils with alluvial clays (fig.3, 4-C1+2, located at the edge of a Bas-Fonds) acting as aquifuge result in an interflow, which is flowing inside the Bas-Fonds towards the water courses.

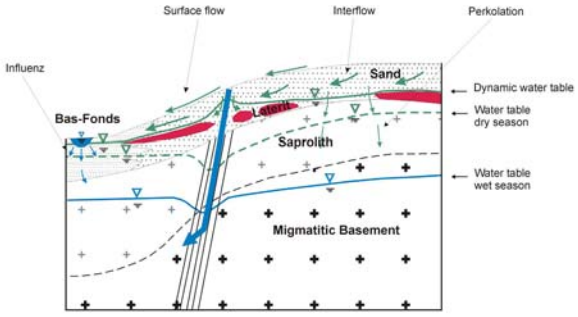

Figure 3. Conceptual hydrogeological model

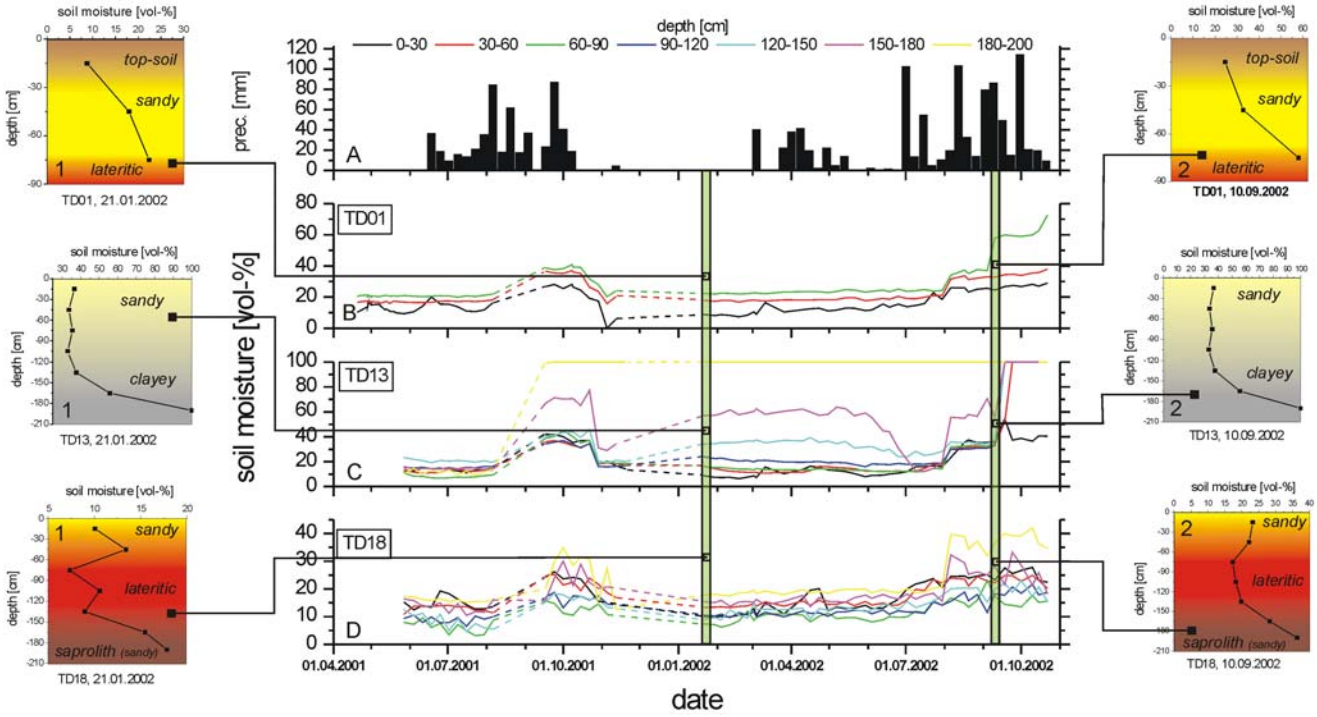

Figure 4. Spatial and temporal development of soil water content at 3 selected sites in the working area. A shows the precipitation, B-D gives the results of TDR measurements in the different locations. The 6 diagrams at the sides (1&2) show the soil moisture content at selected dates in dry (left) and wet (right) season with respect to lithology.

Groundwater recharge can of course only take place in times with high soil water contents which lasts in the working area from mid-August to mid-October (fig.4).

HYDROGEOCHEMISTRY

Beside the quantification of the water content the water quality has been observed. So far, the two village wells and three additionally drilled boreholes were taken as representative for the groundwater in the migmatitic fractured aquifer. Suction cups have been used for the soil water chemistry. Surface water has been sampled, too. Analyses of the taken water samples include various hydrochemical parameters (fig.5) and the isotopic content (^{2}H, ^{18}O, ^{3}H). Artificial tracer tests (Uranine, Sulforhodamine B) both in the unsaturated and saturated zone as well as pumping tests have been performed to determine the hydrogeological parameters. The analysis of the tracer tests is still ongoing.

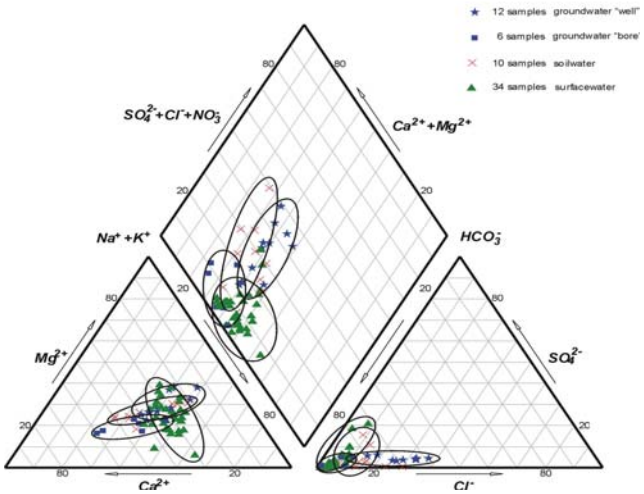

Figure 5. Piper diagram of analytic results of water samples in the Aguima test site.

On account of the hydrogeochemistry, groundwater, soil water and surface water can be clearly distinguished. The groundwater chemistry deviate considerably from the observed soil water chemistry and points to a major groundwater inflow from other recharge areas. The ^{18}O–content of groundwater provides some evidence for recharge by evaporated water. Prolongation of the time serves with additionally samples taken in 2002 might prove the current hypothesis of recharge from surface water.

ACKNOWLEDGMENTS

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REFERENCES

Diekkrüger B, Bormann H, Fass T, Giertz S, Junge B, Reichert B, Skowronek A (2002) Soil water dynamics, surface runoff, groundwater recharge and soil degradation on local to regional scale. In: GSF – Forschungszentrum für Umwelt und Gesundheit GmbH, Projektträger des BMBF für Umwelt- und Klimaforschung - GLOWA Statusreport 2002, 72-75

Riparian groundwater processes in an upland fractured aquifer, mid-Wales, UK: implications for stream flow generation and water quality

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A b s t r a c t : Upland streamflow generation has traditionally been thought to be a simple rainfall-runoff mechanism. Hydrochemical studies prompted the establishment of a detailed field study to assess the importance of bedrock groundwater in streamflow processes. Results from this physico-chemical study showed groundwater near the river to be both unconfined near the surface and confined in depth specific horizons deeper in the profile. However, rapid responses to rainfall in all (including confined) boreholes at the study site indicated rapid recharge pathways further upslope. The different flow pathways and travel times resulted in a different chemical character of groundwaters in different fractures. Bedrock groundwaters were shown to discharge into the stream from these different fractures. Groundwater upwelling into the soils was also observed at some locations indicating soil water to be sourced from (a mixing zone for) both groundwater and rainfall. The role of groundwater in upland streamflow generation is far more complicated than previously considered and has important implications for upland water quality.

INTRODUCTION

Streamflow generation in hard-rock upland regions has generally been modelled as a simple "black-box" rainfall-runoff process where the dominant flow pathway is through the surface layer, purely because of the rapid streamflow response to rainfall. However, attenuation of the streamflow chloride signal when compared to rainfall inputs (Neal *et al*. 1988) has suggested the presence of a hydrochemical "mixing-pot". More recent studies have highlighted the potentially important role of groundwater (a component generally ignored) in streamflow generation (Shand *et al*. 2001). Despite new evidence to the contrary, many hydrologists are still enamoured with the rainfall-runoff concept for explaining/modelling upland streamflow processes. The concept of a hydrological reservoir (a "mixing-pot" for old and new water) involved in streamflow processes is fundamental for accurately explaining and modelling catchment response. The objective of this study was to identify the "mixing-pot" and to understand its role in streamflow generation.

METHODS

A detailed physico-chemical study was set up in the forested Plynlimon catchment in mid-Wales, UK. Borehole geophysics indicated an active shallow groundwater system in the bedrock to depths of at least 10 m. Based on these results, an experimental plot (c. 40 x 40 m) enclosing the stream riparian zone and lower hillslope was intensively instrumented in order to study soil, stream and groundwater pathways and mixing processes. The interaction of soil water and groundwater was monitored using logging Pressure Transducer Tensiometers (PTTs) along a transect perpendicular to the stream channel. The PTTs were installed at approximately 0.1 m, 0.25 m and 0.4 m depths at each of the 4 equipment nests (A-D). Aquifer characterisation was through boreholes (along the same transect) that were sealed to specific depths using novel techniques in order to isolate and sample any groundwater stratification. Groundwater processes were monitored at approximately 1.5 m, 10 m and 25 m depths in each of the 4 nests (Fig.1) by pressure transducers. All data were logged hourly.

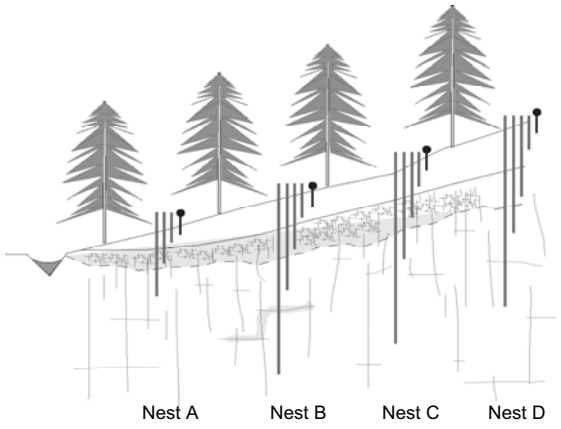

Figure 1. Schematic representation of the nested instrumentation

RESULTS AND DISCUSSION

Water levels measured in many of the boreholes were artesian to differing degrees indicating different water bearing horizons/fractures isolated by confining layers. The physical confinement at the study site was also reflected in the groundwater chemistry (Shand and Haria 2003). However, both shallow (younger) and deep (older) groundwaters show a rapid response to rainfall events; a hydrostatic response to rapid recharge further upslope (Fig.2). The near identical response between deep and shallow groundwaters to rainfall indicates

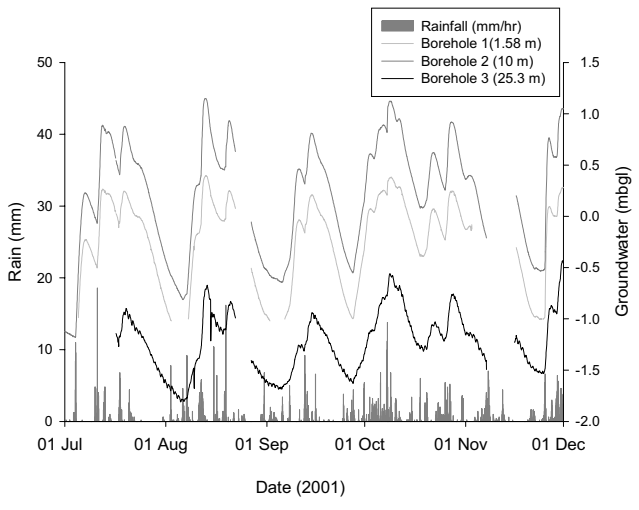

Figure 2. Time series groundwater level responses to rainfall in Nest D

potential connections (and therefore mixing) between the different water bearing strata further upslope that become confined in discrete fracture systems close to the river.

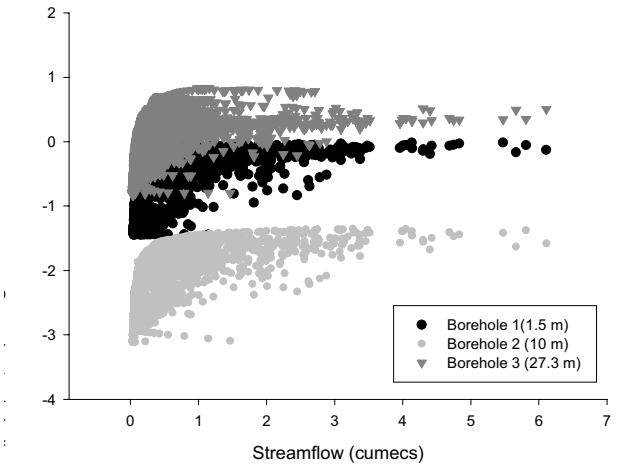

Figure 3. Relationship between streamflow and groundwater levels in Nest C

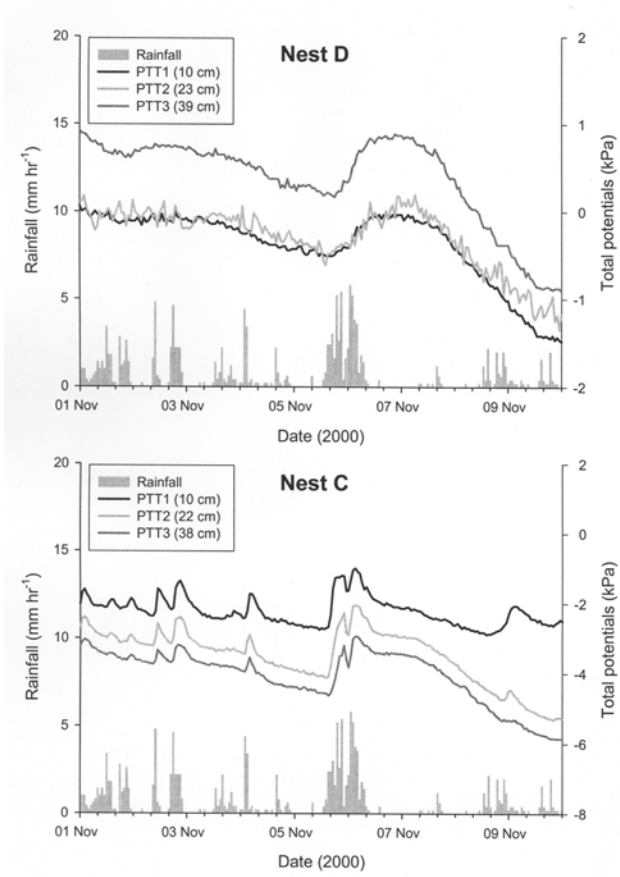

Figure 4. Time series PTT data showing changes in soil water potential at 3 depths in response to a rainfall even in November 2000 at Nest D and Nest C

In this study, groundwater discharges from the 1.5 m and 10 m depth fracture systems were directly into the river at the study site. Fig.3 shows the relationship between streamflow and groundwater level responses. For all boreholes, groundwater levels reached a maximum plateau regardless of increasing streamflow. This data suggests groundwater discharge to streamflow from the deeper (~25 m) aquifer in addition to the shallower groundwater discharge observed at the site. Because of the extremes in chemistry between the deep (~25 m) and shallow (~1-10 m) groundwaters the relative contributions of each component to streamflow mean the implications for water quality are significant.

Soil waters in these supposedly sealed upland catchments are thought to be derived solely from rainfall and have been assumed to be the source of upland storm response. This is because of the rapid streamflow response to rainfall and high aluminium concentrations. However, PTT data (Fig.4) describing soil water potential changes in response to a storm event in November 2000 for Nests D and C give a more complex heterogeneous picture. The data show the highest hydraulic potential in Nest D (furthest from the river) recorded by the deepest (39 cm) PTT with potentials becoming more negative closer to the soil surface. The upward gradient indicates upward water movement from the shallow groundwater in the weathered zone. The response to rainfall is also damped in comparison to the responses observed from the PTTs at Nest C, where the potential responses closely follow rainfall patterns. In addition, the soil water potential gradient is vertically downward at Nest C (Fig.4) indicating vertical water movement down the profile. The results describe groundwater upwelling into the soils at Nest D moving down slope to Nest C (observed as surface runoff during rainfall periods), mixing with rainfall derived soil water, and then moving vertically down the soil profile at Nest C. Hence, the long standing argument of soil water being derived solely from rainfall is questioned by the information from the PTTs which suggest the soils are a mixing zone for water derived both from groundwater and from rainfall.

CONCLUSIONS

Traditional concepts of upland streamflow generation are being questioned by results from this physico-chemical process study. Groundwater processes that until recently had been thought to be of minor significance are coming to the fore with respect to upland hydrological mechanistic processes and may well prove to be the dominant controls in storm flow response. Further assumptions of soil water being only rainfall derived water are challenged. The rapid responses in groundwater levels and evidence for sub-surface mixing indicate that a careful reassessment is required of streamflow generation processes in upland catchments classed as impermeable. The results show that postulated streamflow generation mechanisms that do not take account of groundwater interactions will be fatally flawed.

REFERENCES

Neal C, Christophersen N, Neale R, Smith CJ, Whitehead PJ, Reynolds B (1988) Chloride in precipitation and streamwater for the upland catchment of river Severn, mid-Wales; some consequences for hydrochemical models. Hydrological Processes 2:155-165

Shand P, Haria A (2003) Surface-ground water interactions in an upland fractured aquifer system: implications for the role of groundwater in streamflow generation. This volume

Shand P, Darbyshire DPF, Gooddy DC, Darling WG, Neal C, Haria AH, Dixon AJ (2001) The application of Sr isotopes to catchment studies: The Plynlimon upland catchment of Central Wales. In: Cidu R (ed) Water-Rock Interaction 10 - Tenth Int Symp Water-Rock Interaction, Sardinia, Italy, Balkema, Rotterdam, 1577-1580

Important role of deep-seated hard rocks in the global groundwater flow: possible consequences

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Abstract: Hydrogeologic conditions reflect present-day geodynamic conditions and their development in the geologic history. In this way conditions of groundwater flow, having changed in space and time, have been formed and determined. Three zones, from the ground surface downwards, often designated as the zones of local, intermediate and regional groundwater flow have been defined by several authors and are generally accepted. Similarly to this vertical hydrodynamic zonality and in the same direction, vertical changes in groundwater quality have been determined. Climatic conditions have considerably influenced origin of groundwater chemical composition during the geologic history as well. Due to changing natural conditions a complex and dynamic system of groundwater flow and groundwater quality has been developed mostly as a result of gravity-driven flow. In spite of extreme near-surficial changes, quite regular character of hydrogeologic conditions, manifested by vertical hydrodynamic and hydro(geo)chemical zonality can be found all over the world This complex hydrogeologic system forms part of a global (planetary) groundwater flow system where deep-seated crystalline rocks play important, perhaps decisive role. Consequences of the deep planetary groundwater flow that have resulted in gradual changes of sea-water salinity during the long geologic history cannot be excluded.

INTRODUCTION

From the viewpoint of planetary geodynamics, within the upper part of the Earth's crust in a global scale, stable regions (cratons: shields and massifs) and unstable ones (zones of plate collisions, lineaments, rift zones) are mostly distinguished. While the stable regions mostly underlie extended areas of the Earth's surface, unstable zones typically follow relatively narrow belts.

Regarding hydrogeology, in stable regions and based on distinct approaches, different authors distinguish different types of hydrogeologic environment. Two of them, hydrogeologic massifs (shields) and hydrogeologic basins, represent the basic, very distinct types. The latter sometimes cover very extended areas at the land surface, and reach to maximum depths of more thousand meters. Hydrogeologic massifs, mostly represented by old crystalline rocks, outcrop in extended areas but also underlie the hydrogeologic basins.

HYDROGEOLOGIC BACKGROUND

For more reasons, attention of hydrogeologists has mostly been focused on hydrogeologic basins. Within hydrogeologic basins and, in accordance with general hydrogeologic concepts, extension, depth and rate of groundwater flow, mostly three vertical zones are schematically defined by distinct authors (among others Ignatovitsh 1945, Marinov et al. 1978, Toth 1999). These zones are designated, from the ground surface downwards, as the zones of local (intensive, shallow), intermediate (retarded) and regional (slow or negligible, deep, stagnant) groundwater flow. Similarly to the vertical zoning of groundwater flow (so called vertical hydrodynamic zonality) quite regular vertical changes in chemical composition of groundwater have been expressed by a vertical hydro(geo)chemical zonality in deep hydrogeologic basins. In the shallow zone calcium/magnesium and bicarbonates/sulphates typically prevail in groundwater, except for arid climatic zones where soil and groundwater salinization often occurs. To the depth, sodium and bicarbonate increase while in the deepest parts of hydrogeologic basins sodium/calcium and chlorides prevail. These chemical changes of groundwater are accompanied by general depth-related increase in TDS and water temperature.

Recently, the same general hydrogeologic features and vertical hydrogeologic zonality have been proved also in deep-seated zones of crystalline rocks (hydrogeologic massifs). In different regions all over the world crystalline rocks were found permeable to some degree even in depths of more thousand metres, containing brines without any exception (e.g. Ingebritsen, Sanford 1998, Stober, Bucher 2000). Still an important question remains: what is the vertical depth-related decrease in permeability of these rocks within the deep-seated "massive" zone? And does such a decrease occur at all? It might be quite logical that deep fractured zones in crystalline rocks are better permeable than deep parts of sedimentary basins where deposits are subjects of compaction and consequent subsidence. The differences between the two basic hydrogeologic environments are proved by relatively frequent oil and gas deposits in basins and occurrences of thermal waters in crystalline rocks; the former request presence of tight hydrogeologic barriers enabling hydrocarbons entrapment, the latter, on the other hand, deeply reaching and well permeable fractured systems enabling rapid and concentrated upward flux of thermal waters. This evidences that fractures at least in some types of crystalline rocks (mostly of granitic types) can reach in such a "brittle" environment into large depths. Following the above mentioned considerations two important conclusions can be drawn:

1) Permeable deep hardrock zones enable groundwater flow even though, due to general conditions, typically very slow. Geologic time-scales are to be considered, i.e. up to millions, tens and in some cases perhaps hundreds of million years.
2) Brines of different chemical character (mostly of sodium-calcium-chloride types) occur everywhere in deep hardrock zones, similarly as in hydrogeologic basins, as previously suggested by Gavrilenko, Derpgol´c (1971) who designated this globally extended zone as a "hydrochlorosphere". Origin of these brines, however, has been subject of discussion.

PALEOHYDROGEOLOGIC DEVELOPMENT

If we accept deep-seated groundwater flow that had occurred in such long intervals we have to admit that similar processes and origin of respective groundwater reached until very remote geologic periods. During these intervals and because of former movement of particular parts or even the whole continents throughout the long geologic history, different regions of our present-day world had been exposed to very variable climatic conditions (Schwarzbach 1974). In this way climatic conditions could considerably influence origin of groundwater chemical composition during the geologic history as it is common under present arid conditions. In spite of present-day extreme near-surficial changes in groundwater properties, caused by different Earth climatic zones, quite regular character of hydrogeologic conditions, manifested by vertical hydrodynamic and

hydro(geo)chemical zonality can be followed all over the world. This situation was enabled by formation of brines in extended regions and throughout long periods (in geologic time scales). After the original idea of Filatov (1956) on gravity-driven flow presence of a vertical hydrochemical zonality, together with depth related increase in TDS can be explained and accepted as of a planetary character (e.g. Marinov et al 1974, 1978, Toth 1999).

During very long intervals and under all the time changing natural conditions a complex and dynamic system of groundwater flow and groundwater quality has been developed, influenced by different geodynamic processes. In geologic history several paleohydrogeologic cycles can be defined. Paleohydrogeologic conditions, however, have developed diversely in geosynclines and other zones of accumulation of thick layers of deposits and in geologically stable regions. While in the former Karcev (1972) distinguished sedimentary (elision) and infiltration stages, Krásný (2001) defined in latter accumulation, leaching and anthropogenic stages (comp. Fig. 1).

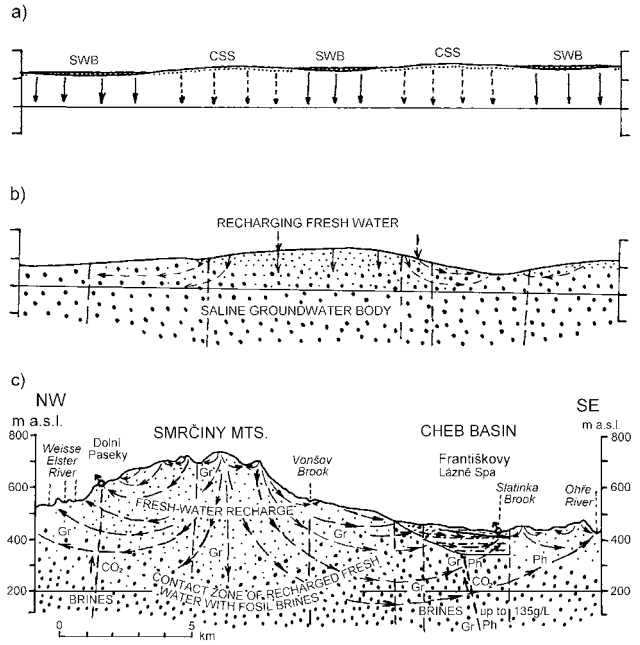

Fig. 1 Possible paleohydrogeologic development in crystalline regions (example from the Bohemian Massif)

a) **Accumulation stage:** downward leakage of brines from saline surface-water bodies (SWB) and from continental soil salinization (CSS)

b) **Beginning of the leaching stage**: leaching of previously accumulated brines by recharging fresh water in elevated areas

a), b) out of scale

c) Leaching + anthropogenic stages (recent situation): example from the West-Bohemian mineral-water region; Gr - granite, Ph - phyllite, CO_2 - ascending CO_2

CONCLUSIONS

Based on results of recent deep drilling, synopsis of present regional hydrogeologic conditions in extended arid zones and paleohydrogeologic analysis of possible development of present-day temperate climatic zones during the geologic history, the author presents a concept of a global groundwater flow summarised as follows:

a) Vertical hydrochemical zonality occurs everywhere in the upper (brittle) part of the Earth's crust, analogously in hydrogeologic basins and in hydrogeologic massifs.

b) Deep-seated brines are mostly of syngenetic or postgenetic exogenous origin, as a result of repeated leakage of highly concentrated surface saline waters (brines), products of arid or semi-arid climatic conditions, into deeper Earth's zones during long geologic periods. After the "accumulation" stage brines have been preserved under platform development conditions or leached by recharged water after a tectonic-geomorphologic rejuvenation.

c) Such a process might stimulate a gravity-driven groundwater flow, having reached to considerable depths - even though very slow one, from elevated regions towards the topographically low areas that usually represent zones of groundwater discharge. The phenomenon has also supported everywhere-occurring vertical hydrodynamic and hydrochemical zonality.

d) In addition to the intricate, generally accepted system of local, intermediate and regional groundwater flow (and respective zones), the deepest and the most extensive part is represented by a global (planetary) groundwater flow that discharges into seas and oceans - planetary discharge zones. Deep-seated crystalline rocks play important, perhaps decisive role in this global groundwater flow.

e) Ascendant flux of hydrothermal fluids in unstable zones of the earth's crust, owing to its limited extension, can be considered rather anomalous compared with the world-wide pattern of a global groundwater flow.

f) As a major consequence of the global groundwater flow lasting for geologic eras changes in sea water salinity could be considered that have occurred in the past and can be anticipated in a very remote future.

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REFERENCES

Filatov KB (1956) Gravitational hypothesis of formation of groundwater chemical composition in platform depressions. Izdat. AN SSSR. 208 pp

Gavrilenko ES, Derpgol´c VF (1971) Deep-seated Earth hydrosphere (in Russian). Naukova Dumka. Kiev. 272 pp.

Ignatovitsh NK (1945) To the question of oil deposits origin and conservation (in Russian). Dokl.Akad.Nauk SSSR 46,5:215-218

Ingebritsen SE, Sanford WE (1998) Groundwater in geologic processes. Cambridge University Press. 342 pp

Karcev AA (1972) Hydrogeology of oil and gas deposits (in Russian). Nedra, Moskva.

Krásný J (2001) Carlsbad mineral water origin in context of Post-Variscan development in Central Europe. In: Seiler KP, Wohnlich S (eds) New approaches to characterising groundwater flow - Proc 31 IAH Congress Munich:989-993. Balkema, Rotterdam

Marinov NA et al (1974) Hydrogeology of Asia (in Russian). 576 pp.

Marinov NA et al (1978) Hydrogeology of Africa (in Russian). 372 pp.

Schwarzbach M (1974) Klima der Vorzeit..Ferdinand Enke Verlag Stuttgart. 380 pp.

Stober I, Bucher K (eds) (2000) Hydrogeology of crystalline rocks. Kluwer Acad. Publishers. 276 pp.

Tóth J (1999) Groundwater as a geologic agent: An overview of the causes, processes, and manifestations. HJ 7,1:1-1

Analysis of groundwater levels in Subijana Carbonate Unit (Basque Country)

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A b s t r a c t : Previous studies of the Subijana Hydrogeological Unit (EVE, 1996) concluded the lack of a connexion between two of the most important sectors in this unit, i.e, the Langraitz Sector and the Subijana Sector. According to Bonacci´s Method, a hydraulic relationship can be derived when piezometric data in the Subijana Sector are compared to the discharge of the main spring in Langraitz Sector. Furthermore, a study of classified flows in this main spring, using Mangin´s Method, shows that the discharge during low waters is influenced by the Subijana Sector. This study shows that, although no relationship could be derived for high water periods, a hydraulic connexion seems to exist for low water periods between the two sectors. A better knowledge of this influence is of great importance for the proper management of this strategic hydrogeological unit.

The Subijana Hydrogeological Unit (170 km^2, 700-900 mm/year of rainfall), fractured and partly karstified Upper Cretaceous limestones of about 300 m thickness, is divided in 5 sectors by previous studies. This paper is centred on the two most important of them, those around the villages of Subijana and Langraitz (fig.1). The limestones have a monoclinal disposition deeping toward the south, from a water-table to a confined aquifer, allowing regional flows in this direction. The Langraitz sector is mainly drained by a perennial *overflow spring* (average discharge of 460 L/s) close to the Zadorra River. The drainage in the Subijana sector is controlled in high water periods by the Baia River crossing the limestones. In this point an *estavelle* structure exists, working as a spring in high-water conditions and as a swallet in low-waters when Baia river sinks into the aquifer. In previous studies no evident relationship between these sectors was put in evidence.

This aquifer, scarcely exploited, is really interesting because its strategic location, near the city of Vitoria-Gasteiz (250.000 inhabitants), and its important water resources (estimation of 72 hm^3/year for the whole unit). Around 15 wells (up to 300 m deep) are located in the two sectors under consideration. High productivity and *moderate* water level fluctuations (about 10 m) are registered close to the main spring (Langraitz). High productivity but great water level fluctuations (up to 40 m) close to the Baia River. The productivity halfway between the two sectors is very low. Groundwater levels (GWL) are continuously measured in three piezometers (two in the Subijana sector, S2 and S5, and one, L6, in Langraitz) and fortnightly in 10 wells.

Fig.1 shows the general disposition of the limestone unit, the location of springs and piezometers in both sectors, the evolution of the piezometric levels for the year 1999 in both sectors and the discharge from the main spring, at Langraitz. The GWL and discharge data have been treated by different analytical methods. An analysis of the piezometric data in the Subijana Sector shows a clear break at 513.5 m where the level decline of the levels becomes more pronounced.

This is interpreted as the situation when hydraulic disconnection of this sector and the Baia River occurs. After this moment the river sinks all its water into the aquifer. Such hydraulic disconnection with the Baia River allows water from the aquifer to be drained towards a different location. Understanding the break in the piezometric levels is important for understanding the behaviour of the two sectors.

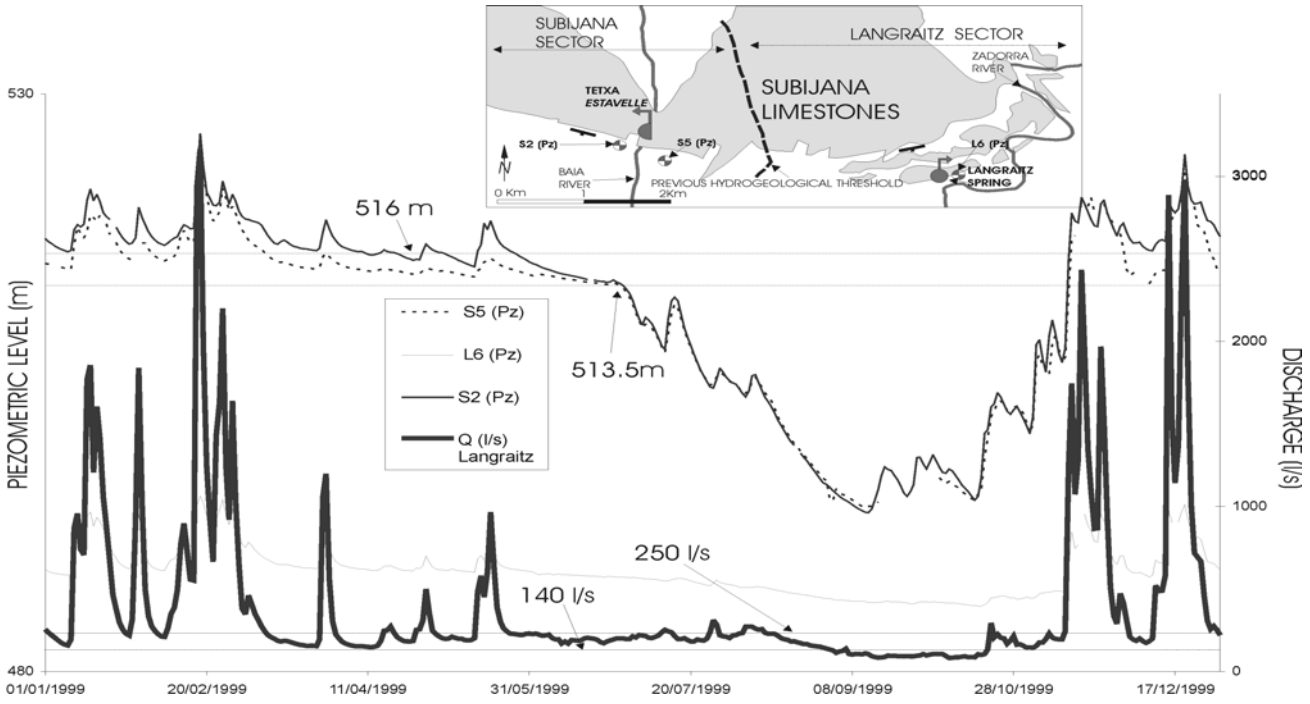

Figure 1. General location, main spring discharge and piezometric data in Langraitz and Subijana Sectors

The discharge of the Langraitz Spring has been correlated to the GWL influencing that discharge, by using the Bonacci´s Discharge Curve Method (1987). Based on this analysis (fig.2) we can define discharge curves which are the result of the *free surface flow* for (1) piezometric data close to the spring (L6 piezometer), and (2) piezometric data in S2 piezometer (Subijana Sector) when its level is higher than 516 m. On the contrary, for piezometric levels in S2 lower than 516 m, and much more when lower than 513.5 m (the break point) the discharge curve has the same characteristics as the *flow under pressure*. This curve can be defined by the equation;

$$Q = a\sqrt{Z},$$

where Q is the discharge, a a constant and Z is the groundwater level elevation respect to the main spring. This curve can be interpreted as a hydraulic influence from the Subijana Sector towards the Langraitz Sector (spring) when the Baia River sinks totally into the aquifer.

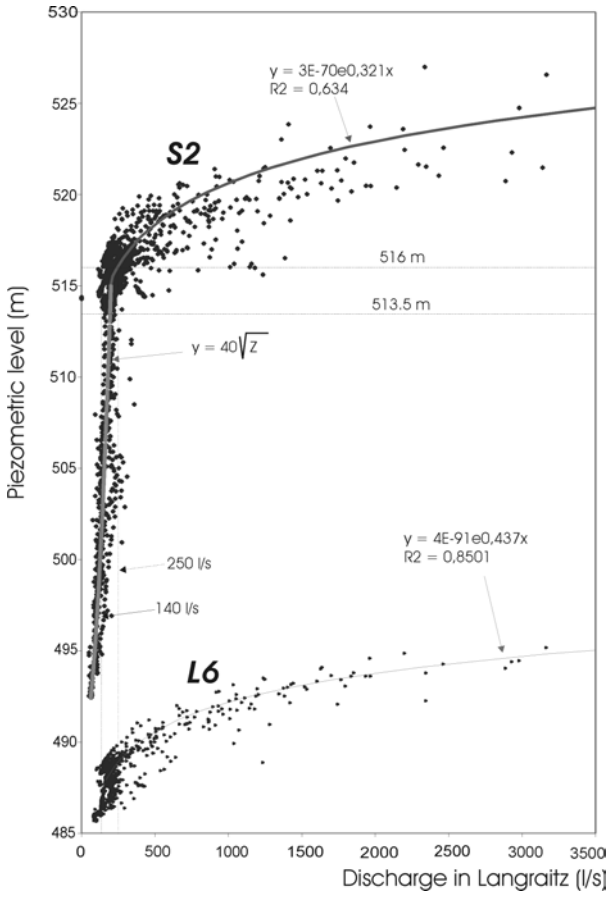

Figure 2. Discharge in Langraitz spring vs. GWL in the Subijana (S2) and Langraitz (L6) Sectors, after Bonacci´s Method (1987)

Probability analysis was applied to both time series, discharge (Langraitz) and GWL (S2), using Mangin´s Method (1971), as shown in fig.3. The discharge analysis shows that there is an increasing of probability for an interval from 140 to 250 L/s that coincides, mainly, with the previously defined *flow under pressure* (fig.2). It could be interpreted as an interval where discharge has a greater probability to be sustained due to influence from Subijana Sector (no influence before). The analysis of the piezometric data (S2) shows that there is a lower probability for levels to sustained when groundwater drops below 513.5 m (break point), as it would be expected if the GWL is really in transition to a new discharge level. In any case, we must be cautious with this interpretation, as relationships are susceptible of being influenced by external parameters. Additional data must be sought in order to obtain a better understanding of the behaviour of the system.

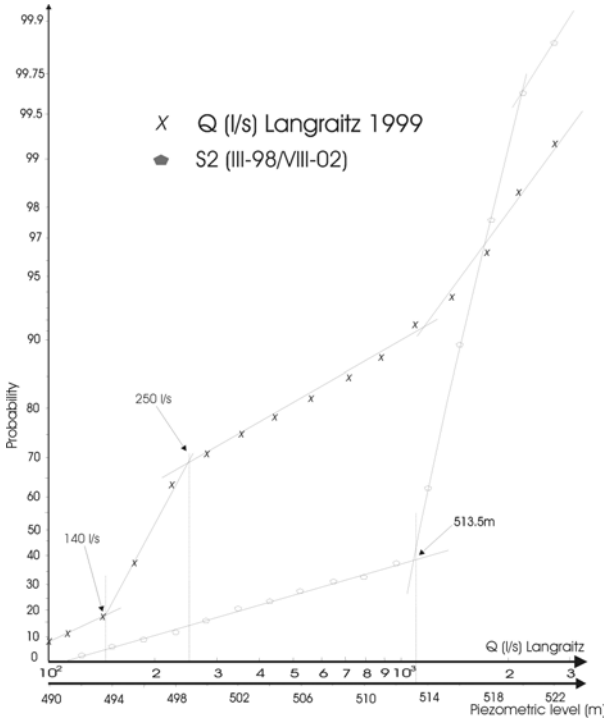

Figure 3. Probability analysis for Langraitz spring vs. GWL in the Subijana Sector, after Mangin´s Method (1971)

The main conclusions of this study are as follows. GWL analysis shows a very homogenous response of the aquifer in the Subijana Sector (Fig.1) where piezometers show a very good image of this behaviour. On the other side, the hydraulic response of each sector is conditioned by the location of its discharge point. In the Subijana Sector, the Baia River controls the GWL fluctuations until the river becomes perched over the aquifer. Then, in low waters, the Subijana Sector influences the discharge of the Langraitz Spring, in the Langraitz Sector. Thus, this partially tapped spring is hydraulically influenced by both sectors. This preliminary result is of great importance due to the imminent exploitation works to be carried out, and must be considered for the aquifer protection schemes.

ACKNOWLEDGEMENTS

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REFERENCES

Bonacci O (1987) Karst Hydrology with special reference to the Dinaric Karst. Berlin, Heidelberg, New York, Londres, París, Tokyo, 184 pp

EVE -Basque Energy Board- (1996) Mapa hidrogeológico del País Vasco. EVE, 377pp + attached

Mangin A (1971) Étude des debits classés d´exutoires karstiques portant sur un cycle hydrologique. Annales de Spéléologie, tome 26, fasc. 2, 283-329

Analysis of recharge mechanisms in the English Chalk using cross-correlation functions

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A b s t r a c t : Groundwater-level response to rainfall was investigated at six sites in the Chalk of Southern England. Daily rainfall and water-level response data were divided into three-month periods and cross-correlated to investigate seasonal variations in water-level response. The full data set for each site was also cross-correlated. For both types of cross-correlation most significant correlations were found to occur in the first month after rainfall input. All significant correlations occurred within seven months of rainfall input. The correlations for each three-month period were compared with the average unsaturated zone thickness during the same period. In general, where the water table is deep (unsaturated thickness > 18 m), the time delay for water-level response increases exponentially as the thickness of the unsaturated zone increases. For shallower water tables (unsaturated zone thickness < 18 m) the water table response occurred, in general, within 48 hours of rainfall input.

INTRODUCTION

The English Chalk is a major aquifer, providing over 40% of total groundwater abstraction in the UK. It is a fine-grained, calcareous, sedimentary rock comprising a porous matrix with pore throat diameters between 0.2 and 2 μm, intersected by fissures of varying size. Low hydraulic gradients and high relief mean that the Chalk unsaturated zone can be more than a hundred metres in interfluve areas. The movement of recharge is delayed in the unsaturated zone; this is partly due to the large thicknesses of Chalk through which it must pass, and also the movement of water into storage on fissure surfaces (Price *et al.* 2000). Wetting fronts tend to disperse over long distances as the water moves through multiple pathways, and this causes damping of the rainfall signal.

There has been much debate as to whether recharge through the unsaturated zone of the Chalk occurs through matric pores or fissures. In this paper we will present cross-correlations of daily rainfall/water table response time series and discuss the implications for Chalk recharge mechanisms. Previous studies of rainfall/water table response data (Headworth 1972) have attempted to relate specific water-table response to individual rainfall events through visual comparison. Cross-correlation provides a more rigorous analysis, enabling statistical correlation at specific time lags to be calculated.

METHOD

The current study focuses on six sites in the Chalk of Southern England. A location map is shown in Fig.1. Rain gauge and water level data for Chilgrove, Preston Candover, Houndean and Broadhalfpenny were available for the two-year period January 2000 to August 2002. Records for Ogbourne were available for September 1991 to May 1995 and for Wolverton from December 1995 to August 2002. Daily water-level data were obtained from borehole loggers; rainfall data were taken from the nearest storage or tipping-bucket rain gauge. The data were divided into three-month periods, (December-February, March-May, June-August, September-November) to investigate seasonal variation in time lag. Longer-term effects were investigated by correlating the entire data set for each borehole.

The daily rainfall data were cross-correlated with the water-level response and statistically significant correlations recorded using eqn.1. This allows the statistical correlation between two sets of data at different time lags to be established. Before the data are analysed, any daily trend in the water-level time series is removed by differencing consecutive values. The cross-correlation between daily rainfall and change in groundwater level indicates the strength of the water table response to rainfall after a certain number of days and the time taken for the first water table response to rainfall.

$$\rho_y(k) = \frac{E[(x_t - \mu_x)(y_{t+k} - \mu_y)]}{\sigma_x \sigma_y} \qquad \text{(Eqn.1.)}$$

k = 0, ±1, ±2…±n
σ_x = standard deviation of x series
σ_y = standard deviation of y series
x_t = observed x value at time t
y_t = observed y value at time t
μ_x = mean of x series
μ_y = mean of y series

RESULTS

The first statistically significant correlation at each site was plotted against the average unsaturated zone thickness for each season (Figs 2 and 3). The time-lag for the first significant correlation between rainfall and water table was found to vary seasonally and between sites. Water-level response tends to occur within a few days during winter recharge periods. At Wolverton and Preston (Fig.2), where the unsaturated zone is <18 m thick, the correlation points display two distinct trends. The first type of response occurs within 48 hrs of a recharge event, and time lag is independent of the thickness of the unsaturated zone. The second type of response occurs after 48 hrs; as the unsaturated zone increases in thickness, the time taken for the first water-level response also increases. The relationship between unsaturated zone thickness and the time delay for the second type of water level response is linear. At Wolverton, (where the unsaturated zone is < 18 m thick) most seasonal responses occur within 48 hrs of rainfall input. At Wolverton, a response after 48 hrs is observed during Summer 01, Autumn 01, Autumn 96 and Spring 98. The range of maximum rainfall intensities during these periods was 20-33.2 mm/day. At Preston, the unsaturated zone is <11 m and the majority of seasonal responses occur within 24 hrs of a rainfall event. At Preston, the correlations that occur after 24 hrs are Spring 00, Summer 01 and Autumn 01. The range of maximum rainfall intensities during these seasons was 26.1-30.3 mm/day.

At Chilgrove, Houndean, Broadhalfpenny and Ogbourne, the unsaturated zone thicknesses vary between 3.23-72.78 m (Fig.3). The majority of correlation points suggest an exponential relationship between unsaturated zone thickness and time lag. Water table response does occur within 24 hrs of rainfall input; however, these correlation points lie close to the exponential

curve. The exponential curve for each site is unique; no general relationship between unsaturated zone thickness and time lag exists for the entire Chalk.

The cross-correlations which were carried out using the entire data set for each borehole showed that, in general, the largest percentage of correlations are observed in the first month after a rainfall event. At Wolverton, Preston, Ogbourne and Chilgrove, no correlations are observed after three months. At three of these sites, the unsaturated zone is less than 10 m thick on average during the monitoring period. At Houndean and Broadhalfpenny, the two sites with the deepest water table, correlations are seen up to seven months after a rainfall event. No correlations occur in any borehole after seven months.

These results suggest that water-level response to recharge can be extremely rapid in the Chalk. The majority of responses observed here are too rapid to be attributed to flow through the matrix, and may be due to the propagation of a perturbation in head or flow through fissures. Work is currently underway to clarify these issues further.

REFERENCES

Headworth HG (1972) The analysis of natural groundwater level fluctuations in the Chalk of Hampshire. Journal of the Institute of Water Engineers, 26:107-124

Price M, Low RG, McCann C (2000) Mechanisms of water storage and flow in the unsaturated zone of the Chalk Aquifer. Journal of Hydrology 233:54-71

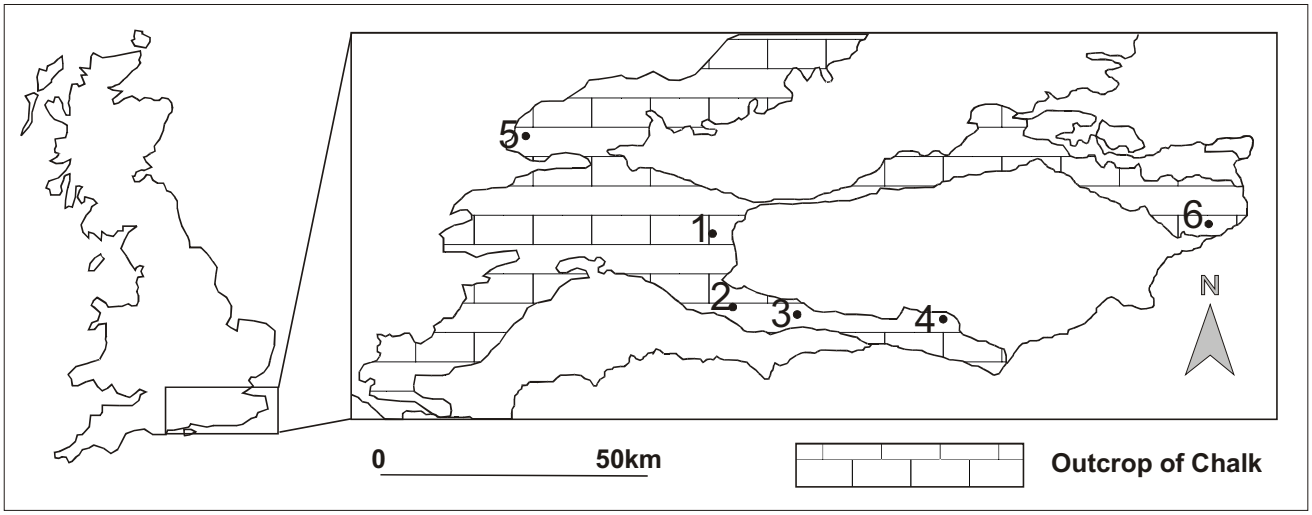

Figure 1. Location of study sites

Legend: 1. Preston 2. Broadhalfpenny 3. Chilgrove 4. Houndean 5. Ogbourne 6. Wolverton

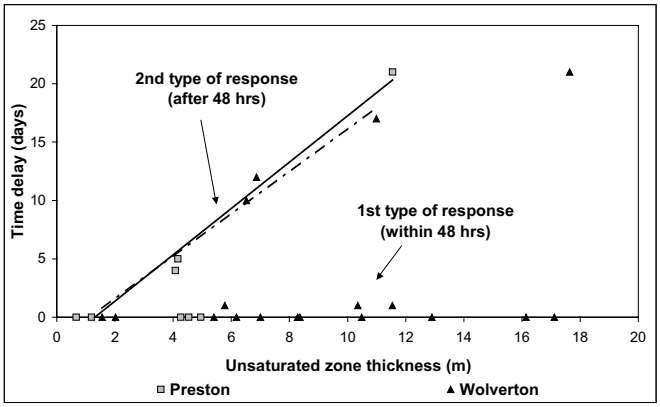

Figure 2. Time lag for first statistically significant water- table response vs. unsaturated zone thickness at Preston and Wolverton

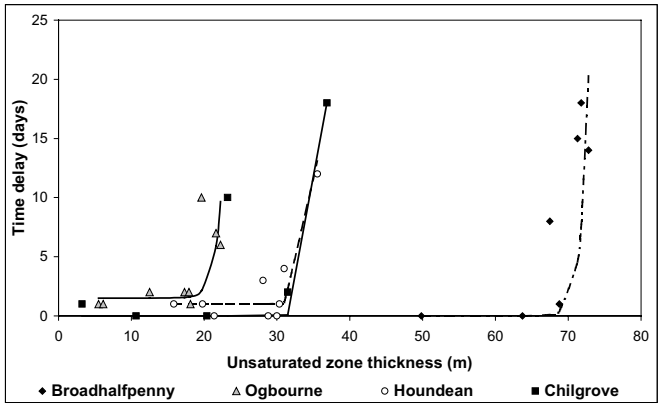

Figure 3. Time lag for first statistically significant water- table response vs. unsaturated zone thickness at Chilgrove, Houndean, Ogbourne and Broadhalfpenny

Ensuring sustainability of wells through dry-season recharge from percolation tanks in hard-rock aquifer regions in India

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A b s t r a c t : Fractured hard-rock aquifers in India mainly include the Pre-Cambrian rocks like the crystalline basement complex and metamorphic rocks, which cover an area of about 800,000 sq. kms of central and southern India. Basalts of western India, (i.e. Deccan traps) of late Cretaceous to early Eocene period, covering an area of about 500,000 sq. kms, are also classified as fractured hard rock aquifers. Major hurdles in ground water development in hard rock areas are the relatively poor ground water resources, low specific capacity of wells, erratic variations & discontinuities in the aquifer properties and the difficulties in exploration and quantitative assessment of the resource. It should, however, be remembered that millions of small farmers in developing countries have their tiny farms in the terrain underlain by fractured aquifers. Whatever small supply available from these poor aquifers is the only hope for these farmers for upgrading their standard of living by growing irrigated crops or by protecting their rain-fed crops from the vagaries of Monsoon rainfall. It is also their only source for drinking water for the family and cattle. In many developing countries, like in India, the 'hard rock hydro-geologists' have, therefore, an important role to play. Monsoon rainfall takes place in about four months of the year (June-September) during which the aquifers get fully recharged. This storage gets depleted in the following, prolonged dry period of four months of winter and four months of summer, due to pumping from dug-wells / bore wells and due to dry-season flow in effluent streams. Recharge augmentation efforts during the rainy season have therefore, an important role to play. However, if the aquifer gets fully saturated, additional infiltration during the Monsoons is rejected. In order to ensure sustainable supply in summer months, the increase in the pumpage for irrigation in the mini-watershed must be compensated by increasing the dry season recharge, if ground water outflow and dry season stream flow are to be kept virtually unaffected. This paper discusses the role of percolation tanks in achieving this objective, through providing dry season or the winter season recharge to the wells in mini-watersheds.

INTRODUCTION

The most significant features of the hard rock aquifers are as follows:

1. A topographical basin or a sub-basin generally coincides with ground water basin. Thus, the flow of ground water across a prominent surface water divide is very rarely observed. In a basin, the ground water resources tend to concentrate towards the central valley portion, closer to the main stream and its tributaries.

2. The depth of ground water occurrence, in useful quantities, is usually limited to a hundred metres or so.

3. The aquifer parameters like storativity (S) and transmissivity (T) often show erratic variations within small distances. The annual fluctuation in the value of T is considerable due to the change in saturated thickness of the aquifer from wet season to dry season. When different formulae are applied to pump-test data from one bore well, a wide range of values of S and T is obtained. The applicability of mathematical modeling is limited to only a few simpler cases.

4. The saturated portion of the mantle of weathered rock or alluvium or laterite, overlying the hard fractured rock, often makes a significant contribution to the yield obtained from a dug well or bore well.

5. Only a modest quantity of ground water, in the range of one cu.m. upto a hundred cu.m. or so per day, is available at one spot. Drawdown in a pumping dug well or bore well is often almost equal to the total saturated thickness of the aquifer.

IMPORTANCE OF DRY SEASON RECHARGE

During the rainy season from June to September the recharge from rainfall causes recuperation of water table from its minimum level in early June to its maximum level in late September. This is represented by the equation:

$$P = R + et + r$$

Where P is the precipitation, R is surface runoff, et is evapo-transpiration during the rainy season and r is the net recharge, represented by the difference between the Minimum storage and Maximum storage in the aquifer. However, after the aquifer gets fully saturated, the additional infiltration during the Monsoons is rejected.

During the dry season, depletion of the aquifer storage in a mini-watershed, from its maximum value to minimum value, is represented by the following equation:

(Aquifer storage at the end of rainy season i.e. Maximum storage) =

(Aquifer storage at the end of summer season, i.e. Minimum storage)

+ (Pumpage, mainly for irrigation, during the dry season from dug wells & bore wells)

+ (Dry season stream flow and underflow supported by ground water)

- (Recharge, if any, available during the dry season, inclusive of return flow from irrigated crops).

The left-hand side of the above equation has an upper limit, as mentioned above. On the right-hand side, the minimum storage cannot be depleted beyond a certain limit, due to requirement for drinking water for people and cattle. Dry season stream flow and underflow supported by ground water have to be protected, as explained earlier, so that the projects depending upon the surface flow of the main river are not adversely affected. Any increase in the pumpage for irrigation during dry season due to new wells must therefore be balanced by increasing the dry season recharge.

The best way to provide dry season recharge is to create small storages at various places in the watershed by bunding gullies and streams for storing runoff during the rainy season and allowing it to percolate gradually during the first few months of the dry season. Such storages are popularly known as percolation tanks. In semi-arid regions, an ideal percolation tank holds maximum quantity by end of September and allows it to percolate for 4 to 5 months. By February or March the tank is dry, so that the water body is not exposed to high rates of evaporation in summer months. Whatever quantity percolates between October and March is available in the wells on the downstream side of the tank even in summer months. Studies carried out in granite-gneiss terrain, have indicated that about 35% of the stored water in the tank percolates as recharge to ground water in the dry season. In basaltic terrain, if the tank is located at suitable site and the cut-off trench in the foundation of tank-bund does not reach upto the hard rock, higher efficiencies upto 50% can be obtained.

Another type of recharge available during the dry season is the return flow from irrigated farms or the percolation below the root zone of crops. This return flow to ground water is usually estimated at about 25% to 30% of the volume of ground water pumped in dry season and applied for irrigation. However, due to increasing popularity of more efficient irrigation methods like sprinkler or drip systems, this type of recharge has a declining trend.

CONCLUSIONS

1.The number of wells and hence the dry season pumpage in many watersheds is increasing due to population pressure. The only way to compensate such increase is to ensure more recharge during the Monsoons as well as during the dry season. Water and soil conservation measures adopted in a watershed ensure recharge augmentation during the Monsoon rains.

2. Small water storages or tanks created in the mini-watersheds by bunding streams and gullies, store runoff water during the Monsoon season and cause recharge to ground water during the next few months of dry season. The residence time of water in the watersheds is thus increased and the percolated water is available in the wells even during the summer season.

3. After a few years of operation, silting of the tank bed reduces the volume of water stored and also the rate of vertical infiltration. Regular desilting of tanks is, therefore, advisable.

Spatial groundwater budget at the watershed scale in a hard-rock aquifer

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A b s t r a c t : In many areas of India, the assessment of groundwater balance at the basin scale is a very important challenge for a better management of this resource stressed by high exploitation through pumping for irrigation. A methodology is presented and applied to a study case in a hard-rock area. The methodology is based on the relationship between balance over a given period and resulting water level fluctuations (Water Table Fluctuation method). It is found that the main positive term of the budget is the return flow from paddy fields irrigation. From June 2001 to June 2002, despite a normal rainfall, the annual balance is a little bit negative, inducing a general water level depletion of 1.18 meters. Decreases of pumping rate or water harvesting measures and artificial recharge on the basin are necessary to inverse this deficit and to insure a sustainable management of groundwater resource.

INTRODUCTION

Supplying 27 million hectares of farmland, groundwater now irrigates in India a larger total area than surface water (21 million hectares). This means it sustains almost 60% of the country's irrigated land. This change in usage in India has been extremely rapid since the 1970s. In just two decades, the groundwater-irrigated lands in India have increased by 105%. In contrast, the areas of surface-water irrigated land rose by only 28% over the same period (1970-1994). A count of mechanized wells and tube wells also illustrates how quickly groundwater irrigation has spread. Numbers of wells have rocketed in the last 40 years, from less than one million in 1960 to more than 19 million in the year 2000. A high stress is put on groundwater specially in (semi-)arid areas such as Andhra Pradesh where surface water is not available. Therefore, it is necessary to adapt the exploitation of groundwater to its availability. For that purpose, it is indispensable to have suitable tools able to assess either the water budget of the aquifer and its renewable reserve.

In this paper, a methodology for water budget evaluation using a database of borewells under a Geographical Information System is presented and applied to a study case in a granitic basin in semi-arid context centred on the village of Maheshwaram in Ranga Reddy district, Andhra Pradesh, India.

COMPONENTS OF THE GROUNDWATER BUDGET

Changes in subsurface water storage can be attributed to recharge, irrigation return flow and groundwater flow into the basin minus baseflow (groundwater discharge to streams or springs), evapotranspiration from groundwater, pumping, and groundwater flow out of the basin (adapted from Schicht and Walton 1961):

$$R+RF+Q_{on}=ET+PG+Q_{off}+Q_{bf}+\Delta S \quad (1)$$

where R is groundwater recharge; RF is the irrigation return flow; Q_{on} and Q_{off} are groundwater flow onto and off the basin, ET is evaporation from the saturated zone; PG is the abstraction of groundwater by pumping, Q_{bf} is baseflow (groundwater discharge to streams or springs) and ΔS is change in groundwater storage. Due to high water table depth in the Maheshwaram basin, no spring is present and there is no contribution of groundwater to streams, consequently the baseflow can be neglected in (1); also vegetation is not able to consume groundwater and evapotranspiration should be redefined as evaporation from groundwater, thus, the term ET is replaced by E: evaporation
The equation (1) can be written:

$$R+RF+Q_{on}=E+PG+Q_{off}+\Delta S \quad (2)$$

The methodology used to determine the components of the budget is the Water Table Fluctuations (WTF) method that links the change in groundwater storage ΔS with resulting water table fluctuations Δh: $\Delta S = \phi \Delta h$ (3)
with ϕ the storage (porosity) of the unconfined aquifer.

Pumping flow

Paddy fields and other crops (vegetables and fruits) are irrigated using groundwater for practical reasons: low rate of drilling and electricity costs, possibility to get water near the crop, etc. A database of the borewells present in the basin has been constituted between June 2001 and September 2001. Exactly 929 wells were located using portable GPS and their discharge rate measured. Information about daily duration of pumping and annual number of pumping days was gathered in order to assess annual abstracted volume. The daily duration of pumping is dependant on power availability. Automatic water level recorders installed in 3 observation wells of the basin allow us to observe water level fluctuations due to pumping cycles and identify an annual average of 6 hours of pumping per day during 365 days.

Horizontal flow across the boundaries of the basin

Because weathering cover of the geological profile is dry and permeability of the fresh basement is very low, horizontal flows in these layers of the aquifer can be neglected. They are located in the fissured layer of the aquifer only. These flows are dependant on horizontal permeability, thickness of saturated zone and local hydraulic gradient. They were computed using a finite differences model in order to obtain a spatial distribution on a grid of squared cells. Modflow model was used with a kriged grid of the altitude of the summit of the fresh basement, constituting the bottom of the aquifer, along with the grid of water table. Hydraulic potentials were imposed on the four limits of the modelled domain, far away from the basin. Flows are computed during a few days with an average horizontal permeability $K=0.87 \times 10^{-5}$ m/s determined by upscaling (from slug-test scale to 200 x 200 meters cells scale) using a DFN (Discrete Fractures Network) model, on the basis of 25 slug-tests.

The balance between horizontal in- and out-flows is positive (specially during pre-monsoon period) due to the capture of water from outside induced by pumping.

Evaporation from groundwater table

This component is evaluated using the relation developed by Coudrain *et al.* (1998). Evaporation flux is expressed as an inverse power function of the piezometric depth below the soil surface, independently of the soil characteristics. It was calculated for both pre- and post-monsoon periods. Due to high depth of depleted water table, the average value is only about 1.7 mm/yr, very less compared to other components of the water budget.

Return flow from irrigation

Most of the pumped water in the basin being used for irrigation, a large part of this volume returns back to the aquifer by direct infiltration in the irrigated lands. Because return coefficient is different from paddy fields to other crops, the global return coefficient is weighted by the repartition of crops. In granite areas

of Andhra Pradesh, the coefficient for paddy fields was evaluated to be 0.60 (APGWD 1977). For other crops, the proposed coefficient is COTHER = 0.20 (CGWB 1998). With 79 % of paddy fields and 21 % of other crops, the final value is C = 0.516.

SPECIFIC YIELD (DRY SEASON BUDGET)

The studied hydrological year (June 2001 to May 2002) was divided into two parts: the wet season (from June to November 2001) corresponds to the monsoon influence with recharge reaching the aquifer while the dry season (from November 2001 to June 2002) starts after monsoon and, by definition, is characterised by the absence of recharge. Following this definition, recharge can be neglected during dry season and the groundwater budget (2) of the basin can be written:

$$RF^{dry}+Q_{on}^{dry} = E^{dry}+PG^{dry}+Q_{off}^{dry}+\Delta S^{dry} \quad (4)$$

where ΔS^{dry} is negative. Applying WTF method to the dry budget, the porosity of this unconfined aquifer is obtained introducing (3) in (4):

$$\phi = (RF^{dry}+Q_{on}^{dry}-E^{dry}-PG^{dry}-Q_{off}^{dry})/\Delta h^{dry} \quad (5)$$

All the terms of (5) were listed above, and estimated for the full hydrological year. Consequently, considering that the duration of dry season is 5 months, the flows for this period are estimated as a ratio (5/12) of the total year. The application of this technique allows us to estimate the specific yield of the aquifer (tab.1). The obtained specific yield is realistic for such fissured granite and is consistent with values found using pumping tests (Maréchal *et al*. 2002) or global modelling.

Table 1. Groundwater budget during dry period (flow terms are in mm/yr)

RF^{dry}	Q^{dry}	E^{dry}	$Q_{on}^{dry} - Q_{off}^{dry}$	Δh^{dry} (m)	ϕ (-)
69	135	1.0	4.9	-6.88	0.0089

RECHARGE (WET SEASON BUDGET)

Accurate recharge estimate is difficult specially in (semi-)arid areas where spatial and temporal variability are high. The chosen technique is a combination of WTF and groundwater budget techniques. Contrary to classical water budget techniques, groundwater budget technique is not dependant on uncertainties on evapotranspiration component. Furthermore, because of the good quality of observation network, the WTF method can be applied at the basin scale. Thus, combining (2) for wet season and (3), the recharge is estimated:

$$R^{wet}=\Delta h^{wet}*\phi-RF^{wet}-Q_{on}^{wet}+E^{wet}+PG^{wet}+Q_{off}^{we} \quad (6)$$

Application of this equation is illustrated at tab.2. The estimated recharge flow includes all recharge types (Direct, Indirect and Localized Recharge).

Table 2. Groundwater budget during wet period (flow terms are in mm/yr)

RF^{wet}	PG^{wet}	E^{wet}	$Q_{on}^{wet} - Q_{off}^{wet}$	Δh^{wet} (m)	R^{wet}
49.6	96.1	0.7	3.5	+5.70	94.5

ANNUAL GROUNDWATER BALANCE

The annual groundwater balance was calculated from June 2001 to June 2002 (Tab.3).

Table 3. Annual groundwater budget (flow terms are in mm/yr)

R	RF	PG	E	$Q_{on} - Q_{off}$	ΔS	Δh^{tot} (m)
94.5	119	231	1.7	8.4	-10.5	-1.18

Considering the uncertainty on the flow components, this indicates that the budget is more or less balanced. However, the total balance is a little bit negative, in accordance with an average water level decrease of about 1.18 meters on the basin during this period, in spite of a normal monsoon (603 mm of rainfall). This clearly shows that, with such an abstraction rate on the basin, any bad monsoon as for example the monsoon of this year (2002), will induce a significantly negative balance followed by a depletion of water table. The map of water budget (fig.1) shows that negative balance areas only correspond to pumping areas due to the fact that pumping flows and return flows are respectively the main negative and positive components of the budget. In spite they represent only 25 % of the 1324 cells the whole balance is negative.

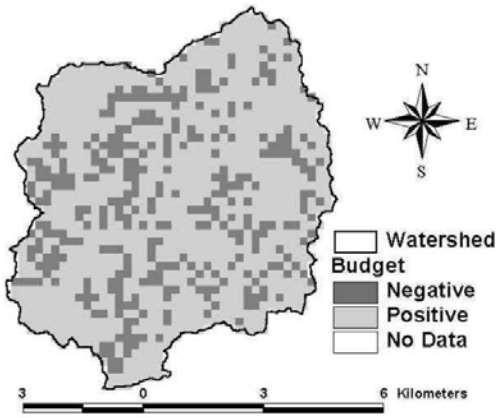

Figure 1. Spatial annual budget

CONCLUSIONS

The annual groundwater budget of Maheshwaram basin was calculated from June 2001 to June 2002. The global balance on the whole basin is a little bit negative, inducing a depletion of 1.18 meters for the water table in spite of the occurrence of a normal monsoon. This means that high rate of pumping leads to overexploitation of groundwater resource at the basin scale. The importance of irrigation return flow is arisen in such a typical rural basin in semi-arid southern India.

REFERENCES

APGWD (1977) Studies on hydrologic parameters of groundwater recharge in water balance computations, Andhra Pradesh. Government of Andhra Pradesh. Ground Water Department, Hyderabad; Research series no. 6

CGWB (1998) Detailed guidelines for implementing the ground water estimation methodolog. Central Ground Water Board, Ministry of Water resources, Government of India

Coudrain-Ribstein A, Pratx B, Talbi A, Jusserand C (1998) Is the evaporation from phreatic aquifers in arid zones independent of the soil characteristics? C.R. Acad. Sci. Paris 326:159-165

Maréchal JC, Wyns R, Lachassagne P, Subrahmanyam K (2002) Vertical Anisotropy of Hydraulic Conductivity in the Fissured Layer of Hard-rock Aquifers due to the Geological Structure of Weathering Profiles, submitted to Journal of the Geological Society of India

Schicht RJ, Walton WC (1961) Hydrologic budgets for three small basins in Illinois. Illinois State Water Surv Rep Invest 40

Groundwater recharge estimation in data-scarce fractured rock aquifers: examples from Ireland

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A b s t r a c t : The hydrogeology of Ireland is dominated by fractured bedrock aquifers with a variable covering of Quaternary deposits (mainly tills). Flow systems are complex and there is relatively little detailed information available on groundwater recharge. Improved understanding of recharge will be required for the proper management of groundwater resources within the proposed river basin districts to be delineated under the new European Water Framework Directive. Most recharge estimates in Ireland are based on soil moisture budgets or on analysis of baseflow contributions to rivers. This paper examines the uncertainties associated with the soil moisture budget approach and highlights the important influence that the Quaternary tills have on recharge. With the aid of a simple one-dimensional numerical model, it is shown that differences in recharge owing to variations in the root constant or time-step used in the soil moisture budget are much less significant than the effects of varying the hydraulic gradient, permeability or thickness of the till unit. Where the fractured aquifers are overlain by thick, low permeability till, the actual recharge may only be a small proportion of the potential recharge. However, surface runoff from such areas may produce indirect recharge in other parts of the catchment where the tills are thin or absent. Indirect recharge of this type is especially important in karst aquifers.

INTRODUCTION

The uncertainties involved in estimating groundwater recharge and the need for a better understanding of recharge processes were highlighted in the thematic issue of *Hydrogeology Journal* on groundwater recharge, published in 2002 (de Vries and Simmers 2002, Scanlon *et al.* 2002).

In Ireland, the majority of recharge estimates have been based on soil moisture budgets and river baseflow analysis (Misstear 2000). Until recently, it was not considered especially important to have accurate estimates of recharge since groundwater abstractions for water supplies in Ireland represented only a tiny fraction of the available resource. Now, however, owing to growing awareness of the importance of groundwater contributions to the environment and, more specifically, to the introduction of the European Water Framework Directive (European Commission 2000), the availability of reliable recharge estimates is recognised as essential to the proper management of the country's water resources. Fractured aquifers in Ireland are characterised by low storativity and so harmful environmental impacts to groundwater-fed wetlands could arise if future abstractions were to exceed recharge.

The aim of this paper is to describe and quantify some of the uncertainties involved in the soil moisture budget approach and in the estimation of 'runoff losses' due the underlying till and aquifer conditions.

GROUNDWATER RECHARGE

Groundwater recharge may be defined as 'the downward flow of water reaching the water table, forming an addition to the groundwater reservoir' (Lerner *et al.* 1990). Some methods of recharge estimation, including soil moisture budgets, assume that all water moving below the soil zone eventually contributes to recharge. However, this assumption may not be valid if there are lateral flows in permeable subsoils or within fractured bedrock above the water table.

There are two main types of recharge: direct (vertical infiltration of precipitation where it falls on the ground) and indirect (infiltration following runoff). It is generally recognised that in temperate climates most recharge is direct, whereas in arid regions most recharge occurs from surface runoff (Simmers 1997). However, there are some situations in temperate regions where indirect recharge dominates, most notably in karst areas (where recharge occurs from losing rivers and via swallow holes and other solution features).

SOIL MOISTURE BUDGET APPROACH

Soil moisture budgets involve the simulation of soil moisture surpluses and deficits from precipitation and potential evapotranspiration (PE) data. The data are divided into a series of time-steps. For each time-step, the precipitation input is allocated to demands from evapotranspiration and soil moisture storage. The actual evapotranspiration (AE) for each time-step is assumed to equal PE unless the soil moisture levels are below a critical 'root constant' threshold. At storage levels below this threshold, the ability of plants to transpire is assumed to diminish and AE is assigned a value less than PE. If a soil moisture surplus exists after the various demands have been met, the surplus is assumed to comprise groundwater recharge and/or surface water runoff. The soil moisture surplus is also termed 'potential recharge'.

The Aslyng (1965) and Penman-Grindley (Grindley 1969) methods are based on these concepts and both have been used in Ireland (e.g. Daly 1994 and MacCarthaigh 1994). Key variables that influence the predicted amount of potential recharge are the root constant and the soil moisture budgeting time-step. Using one set of meteorological data from Ireland, the authors found that the average annual potential recharge varied from the estimate for pasture by –10% to +20% across a range of simulated vegetation types (i.e. across a range of root constants). Decreasing the time-step from monthly to daily intervals had the effect of increasing the potential recharge by up to 10% for permanent grassland. Although significant, these variations are much less than the uncertainties that result from the influence of the tills themselves on recharge.

Recent enhancements to the basic potential recharge approach have been proposed for the U.K. by Hulme *et al*. (2001). However, using a set of meteorological data from Ireland, estimates of potential recharge for pasture were only 5% less than those derived using the original Penman-Grindley method. This is to be expected, given that the enhancements are more likely to influence potential recharge estimates in areas where summers are dryer and where there is less permanent pasture than in Ireland.

INFLUENCE OF TILLS ON RECHARGE

A soil moisture budget produces a figure for the moisture surplus or potential recharge. In areas where the important aquifers are overlain by till, it is necessary to split this moisture surplus into 'actual' recharge and runoff (or other losses such as interflow).

Wright *et al.* (1982) proposed a series of infiltration coefficients that can be applied to the potential recharge to calculate actual recharge in Irish conditions: 0.2 for poorly permeable clayey till, 0.5 for moderately permeable sandy till and 0.8 for permeable sand and gravel (or thin subsoil). Daly (1994), in his study of the Nore basin, produced slightly different coefficients: 0.3 for thick till or gley soils, 0.6 for thin till and 0.9 for thin permeable soils overlying karst. These coefficients were based largely on regional-scale water balance estimations.

One-dimensional model

A simple one-dimensional numerical model code was developed to examine the interplay of vertical permeability, thickness and hydraulic gradient in a till unit. A reference set of groundwater level data was selected for a borehole in a dolomite aquifer in south-central Ireland. At the borehole, the aquifer is confined by 15m of till. Heads in this data set fluctuate by 3.6m annually. The reference data set was used to model a range of hypothetical recharge scenarios through the till unit overlying the aquifer. A range of till thicknesses and permeabilities was examined. The relative positions of the base of the till and the reference water levels were varied to simulate variations in the hydraulic gradient between the till and the aquifer.

Notwithstanding the simplifying assumptions involved in this modelling, the results provide an interesting picture of the influence of till permeability, saturated thickness and vertical hydraulic gradient on recharge. Increasing till permeability across the typical range found in Ireland had the effect of increasing the predicted infiltration factor by eight to fifteen fold. Decreasing the till thickness across a typical range increased the predicted infiltration factor by two to three fold. For a till of permeability 0.004 m/d, increasing the annual range in vertical hydraulic gradient also increased the predicted infiltration factor by two to three fold. For a similar set of boundary and till conditions, a reduction in infiltration factor with a reduction in gradient might signify, for example, the reduced ability of a poor aquifer to accept recharge as compared to a productive aquifer.

The results of this simple modelling exercise suggest that the actual recharge occurring to aquifers covered by thick, low permeability tills may be 90% to 95% less than the potential recharge simulation for pasture. It is worth pointing out, however, that at a catchment scale, the total amount of recharge from till areas will often be higher than that amount infiltrating directly through the till. This is because indirect recharge will occur once runoff, generated over the till, flows onto more permeable strata. This may help to explain why existing water balance studies in Ireland have generally not predicted infiltration factors of less than 0.2, even in areas of low permeability tills. One example of this effect in Ireland occurs at a site in County Kilkenny, where surface water, which originates as runoff on saturated and moderate permeability tills of 5m to 15m thickness, recharges the limestone aquifer through swallow holes once it reaches an area of thinner till cover (Daly 1994).

CONCLUSIONS

Existing water balance studies, coupled with the simple sensitivity analyses documented in this paper, provide evidence that the permeability of the till, along with its thickness and the vertical gradients with the bedrock, have a very significant influence on recharge across much of the country. Where thick, low permeability tills are present, actual recharge may only be 5 to 10% of the potential recharge.

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REFERENCES

Aslyng HC (1965). Evaporation, evapotranspiration and water balance investigations in Copenhagen 1955-64. Acta Agriculture Scandinavica XV:284-300.

Daly EP (1994) Groundwater resources of the Nore River basin. Geological Survey of Ireland, RS 94/1.

de Vries JJ, Simmers I (2002) Groundwater recharge: an overview of processes and challenges. Hydrogeology J 10:5-17

European Commission (2000) Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Communities, L 327

Grindley J (1969) The calculation of actual evaporation and soil moisture deficits over specified catchment areas. Meteorological Office, Bracknell Hydrological Memoir 38, 3pp

Hulme P, Rushton K, Fletcher S (2001) Estimating recharge in UK catchments. In: Impact of Human Activities on Groundwater Dynamics. Proc. Of Sixth IAHS Scientific Assembly. AIHS Publ 269

Lerner DN, Issar AS, Simmers I (1990) Groundwater recharge: A guide to understanding and estimating natural recharge. International Contributions to Hydrogeology 8, Heise, Germany, 345 pp

MacCarthaigh M. (1994): Summary details of water balances in Glyde, Dee, Finn and Blackwater (Monaghan) catchments for the period December 1975 – November 1977. Environmental Protection Agency, Dublin

Misstear BDR (2000) Groundwater recharge assessment: a key component of river basin management. In: Proc. National Hydrology Seminar on River Basin Management (Irish National Committees of the International Hydrology Programme and the International Committee for Irrigation and Drainage), Tullamore, 21 November 2000, 52-59

Scanlon BR, Healy RW, Cook PG (2002) Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology J. 10:18-39

Simmers I (ed.) (1997) Recharge of phreatic aquifers in (semi-) arid areas. International Association of Hydrogeologists, 19, Balkema, Rotterdam, 277 pp

Wright GR, Aldwell CR, Daly D, Daly EP (1982) Groundwater resources of the Republic of Ireland. Vol. 6 in the European Community's atlas of groundwater resources, SDG, Hannover

Groundwater recharge in central Uganda

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A b s t r a c t : Ugandans prefer groundwater to the abundant surface water for their drinking water supply. The government of Uganda has invested a lot in extracting groundwater for rural communities. However one problem has been identified which limit the effectiveness of groundwater sources. The problem is the contamination of ground water sources by open pit-wells, which are called "Scoop wells". Various measures have been taken to reduce contamination of groundwater sources by the scoop wells. The measures include positioning of protected wells relative to the scoop wells, lining of wells with brickwork, gravel and clay etc.

INTRODUCTION

Despite an abundance of surface water in Uganda (18% of the land area), the predominantly rural (>70%) population relies almost exclusively on groundwater for a potable water supply. This dependence arises from the more wide spread occurrence, superior quality and reduced susceptibility to contamination, of groundwater supplies compared to surface water supplies.

As a result provision of safe water to rural communities in Uganda has depended primarily upon the construction of wells and protection of spring discharges.

Emerging National Water Resources Policy and Strategy

The Water Action Plan and Water Statute have been refined and synthesized explicitly into a draft national water policy.

Objectives and Guiding Principles

The overall policy objective of the Uganda government is "to manage and develop the water resources of Uganda in an integrated and sustainable manner so as to secure and provide water of adequate quantity and quality for all social and economic needs, with the full participation of all stake holders, and so as not to leave future generations any worse off than ourselves".

Groundwater Recharge in Luwero District

Recent research in groundwater resources in Luwero District of central Uganda indicates that most ground-water move by way of shallow weathered soils (regolith) rather than under-laying bedrock fractures which have traditionally been developed.

Indeed, the Baganda people have long relied upon this shallow source through unprotected spring discharges and hand dug "scoop wells".

During the last three years, a number of agencies (WATSAN, UNICEF, CPAR) have constructed shallow wells with competent yields in the regolith for domestic hand pump abstraction rates (=3m^3/day). However incidentals of well failure and waning spring flow have been attributed to presumed fluctuations in shallow well water table and raised concerns over the sustainability of groundwater development programmers in the region. Nevertheless, studies of groundwater recharge in Luwero have show that replenishment is in the order of 0.2m/year and occurs exclusively from intense (>10mm/day) rainfall during monsoons.

Monitoring of water levels in the unconfined regolith aquifer was therefore initiated in June 1994 in order to investigate both the magnitude of water table dynamics in the regolith and the nature of the water table's response to recharge events predicted by developed models of groundwater recharge.

Methodology

- Weekly water levels are noted from the monitored wells in Luwero and Mukono
- Weekly volume of incoming rainfall is also noted in the same areas
- Estimated recharge is determined
- Weekly hydrographs are drawn from the concerned wells.

Findings

Clearly the well hydrographs demonstrate the delayed response for the regolith aquifer to the on-set of the rainy season and hence monsoon-fed recharge.

These preliminary data also appear to support by and large, the magnitude of recharge predicted by the soil moisture balance model of considerable significance is that observed water levels appear to confirm the timing and magnitude of predicted ground water recharge in Luwero. The water level data also suggest that fluctuations of 0.5m occur inn the regolith aquifer. This dynamic may account for the variability in depression spring discharges, which drain the crest of the water and should be considered when positioning screen and gravel packs during the shallow well construction.

Both assertions are however tentative based on very limited time frame over which the data have been collected. It is critical that efforts to monitor ground water levels be continued and extended in order to improved the occurrence, validity and extent of the results.

CONCLUSION

Qualitative hydrogeological studies of the regolith reveal that the unit is considerably more permeable than the underlying bedrock and where substantial thickness exists, it is likely to provide a significant better aquifer.

In Uganda, where the practice has until recently been development of only the bedrock aquifer, the above findings stress the need to develop the regolith aquifer which is likely to provide more sustainable and less costly sources for rural water supplies than the bedrock fractures. This would be possible through construction of shallow wells (augered or dug) in areas where the regolith aquifer are so thick, to provide enough water, deep wells exploiting the bedrock aquifer and screened in the regolith would be more sustainable.

All in all the regolith is very important inn groundwater development, as it is able to raise a cheap and more sustainable source of water supply and can recharge the weaker bedrock aquifer through vertical leakage.

It can also be concluded that the soil moisture balance method of evaluating recharge and hence sustainability of groundwater development programmes, may prove effective in other regions across Uganda and Equatorial Africa.

REFERENCES

Chant DA (ed) (1970) Pollution Probe, new press

Morgan P (1990) Rural Water Supplies and Sanitation. Macmillan Education Ltd. London and Basingstoke

Groundwater resources development in the Decan trap country of the western Ghats, India

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Abstract: Groundwater resources development has been a challenge for the Western Ghats region of the Indian Peninsula characterized predominantly by the basaltic lave flows. This paper discusses few development options relevant to the prevailing hydrogeological situations. On the basis of an analysis of the fracture and lineament patterns and geomorphic features, suggestions have been given for proper siting of the dugwells and borewells. Artificial recharge measures have been suggested for the water-scarcity areas, while consumptive use of water resources has been recommended for the command areas of the irrigation schemes. Measures have also been suggested for development of springs at higher elevations

INTRODUCTION

The Western Ghats hill ranges are one of the major physiographic provinces of the Indian sub-continent running for a distance of 1600 km parallel to the Indian West Coast with an average elevation of 1000-1300 m above mean sea level. These hills are bestowed with heavy precipitation (4000-6000 mm/yr), but the headwater basins coalescing these hills retain very small quantity of groundwater due to poor surface slope conditions. The narrow valleys in these hills offer ample scope for surface water development, and several medium to major irrigation projects have already been constructed in these areas with well-defined canal network. These developments have truly boosted agricultural productivity in the region, but at the same time they have also brought an economic disparity between the command (areas irrigated by these canals) and non-command areas. Water logging problems are also increasingly seen in low-lying areas. While these problems are mainly due to poor groundwater management strategies in the region, it is recommended that the groundwater resources in these headwater basins be properly assessed and suitable measures be taken for a uniform groundwater development. As a first step in this direction, several measures have been suggested, within the framework of the National Water Policy, as a case study for the groundwater resources development in the Koyna River basin, a headwater basin on the east of the main ridge of the Western Ghats. This river basin generally trends north-south and covers an area of 2,036 km^2 in the Deccan terrain of the district of Satara, Maharashtra State, India. Naik *et al.* (2001) give a detailed account of this river basin.

HYDROGEOLOGY

The Koyna River basin represents a typical physiographic set-up characteristic of the Deccan Plateau. Basalt is the primary aquifer, while laterites, alluvium and talus deposits form shallow aquifers of secondary importance. In a typical weathered zone, the basaltic lava flows consist of four water-bearing horizons: (1) black cotton soil with yellow or reddish clay (0.5-8 m); highly weathered and highly jointed basalt (3-10 m); (3) poorly weathered and highly jointed basalt (1-2 m); and (4) poorly weathered and poorly jointed basalt (1-2 m), which overlies the hard massive basalt. The second horizon consists of both weathered vesicular and non-vesicular (massive) basalt, in which the joints in the upper portions are completely filled with clay. Gradually the clay content decreases downward and the joints are more open because of decreasing effect of complete weathering. The lower part of horizon 2 and the complete thickness of horizon 3 have the highest permeability. With greater depth, the joints are closed (horizon 4), and the underlying massive basalt yields little groundwater. Deeper ground water occurs at the basaltic flow contacts, within the vesicular basalts, and in the fractured and jointed sections in a basaltic flow. Ground water occurs under phreatic condition in shallow aquifers (<30 m), while in deeper aquifers (>30 m), it occurs under semi-confined to confined conditions. Transfer of groundwater does take place between the shallow and deeper aquifers, and fractures/lineaments act as conduits for such groundwater movements.

The bulk of the population in the Koyna River basin live in discreet villages, and agriculture is the main occupation in the area. Large-diameter dugwells tapping shallow aquifers are commonly used for drinking and irrigation purposes, while borewells tapping deeper aquifers are used only for drinking purpose. Dugwells are mostly 2-14 m deep; and rarely go up to 25 m deep. Diameters range from 2-10 m; 50% of them have a diameter of 2-4 m. The borewells, mostly 150 mm in diameter are generally 30-90 m deep; most of them are 50-70 m deep.

GROUND WATER RESOURCES DEVELOPMENT

Selection of Well Sites

Indiscriminate selection of well sites yields poor results. About 50% of the borewells drilled in the region either get dry or give poor yield. Only about 20% of them are high yielding (>3000 L/h). Because of the high risk involved in their success, borewells are not very popular by the farmers in the region. On the basis of an analysis of the yields of borewells and dugwells with reference to fracture and lineament patterns and geomorphic features, the following observations could be made.

1. Borewells along or near lineaments have substantially higher yields than those not associated with lineaments. Conversely, in shallow dugwells, lineaments have little influence on well yields.
2. Where two or three lineaments intersect, yields of borewells at those sites are greater than the yields of wells away from lineaments intersections.
3. Borewell yields are higher along the NE-trending lineaments than along lineaments trending in other directions.
4. Borewells intersecting NE-trending lineaments are more high yielding in deeply buried pediments than those intersecting NE-trending lineaments on the dissected plateau. The borewells in such areas have yields as high as 39,000 L/h.
5. Borewells along the NW-trending lineaments are high yielding if a stream is flowing along these lineaments and the borewells are very close to it. The borewells along lineaments in this setting have yields as high as 6,000 L/h.
6. Dugwell yields are related to the type of geomorphic feature. Yields are higher in wells dug in deeply buried pediments than in those dug in shallow buried pediments and dissected plateaus.

Artificial Recharge of Aquifers

Artificial recharge of the aquifers is an answer to the declining trends of the groundwater levels in the dissected plateau and non-command areas. Currently, most of the percolation tanks meant for artificial recharge through downward percolation of stored water lie on poorly weathered and poorly jointed massive basalts in the foothill zones, and do not produce desired results. Poor site selection of these structures due to several field constraints is the main reason for their poor performance. In the future, selection of these sites should be based on thorough investigation of the local geomorphological and hydrogeological conditions. Care must be taken that the percolation tanks lie on moderately or highly weathered basaltic horizons. In some places, these structures need additional deepening to expose these horizons. Creation of artificial fractures through use of explosives on the tank beds, in case they lie on poorly weathered and poorly jointed massive basalts, may help in the downward percolation of surface water. Construction additional structures, such as check dams across smaller streams, may help in greater surface-water retention and consequent lateral and downward percolation of water.

Consumptive Use of Water Resources

Koyna River is a perennial river due to release of water two times in a month from the Koyna dam. About 61 of MCM of surface water is lifted by farmers through several co-operative lift-irrigation schemes for irrigation purposes. Base flow has been estimated as 35 MCM annually in this area (Naik and Awasthi 2003). The high amount of baseflow from an area of 1082 km^2 may be attributed to the over-application of surface water. Groundwater levels are rising alarmingly in the command areas of the lift-irrigation schemes often leading to near water-logging conditions. Consumptive use of water resources is an answer to combat the water logging problems. Some type of local legislation to force farmers to irrigate part of their land through groundwater may help to offset the rising groundwater table. Further, the command area of the lift-irrigation schemes may be expanded into the adjoining scarcity areas to cover larger areal extent and needy areas. Also, during the dry span of the year, the unutilized baseflow can be tapped by constructing additional dugwells, dug-cum-borewells or horizontal trenches or deepening of the existing wells.

Harnessing of Springs

People at higher elevations depend exclusively on springs. On many occasions, these springs are thoughtlessly diverted causing heavy ecological damage and public outcry. The local Government has tapped many of these springs for community water supply. A small tank is constructed at the origin of a spring and water is allowed to flow by gravity through a pipeline to a distribution tank, which is located higher than the village to be served. Depending on the quantity of the water stored, water is released either periodically or continually by pipelines to the villages for their use. Among the 30 water supply schemes investigated, 23 (~80%) were found ineffective (Naik *et al.* 2002). Following are a few suggestions for effective development of these springs.

1. Springs should be tapped after thorough examination of their seasonal discharges, including during the summer.
2. Whenever necessary, two or more springs should be tapped together to cater to the needs of a relatively larger population.
3. After installation of the water-supply schemes, they should be monitored periodically.
4. In case water supply exceeds use, the surplus water may be stored for use in horticulture and to irrigate cropland.
5. Rainwater harvesting structures may be constructed at suitable locations on hilltops for enhancement of the life of springs and to increase their discharges.
6. The pipelines connecting the springs and storage tanks may be buried at about a meter depth so as to protect them from detachments because of rockslides or wildlife interference.
7. A barbed-wire fence may be constructed around the springs for their protection.

CONCLUSIONS

The Western Ghats region is characterized by both scarcity and abundance of groundwater – scarcity in the dissected plateaus and abundance in the command areas of the irrigation schemes, especially in the central portions of the river valleys. The issues involved in the optimal development of the available groundwater resources are: (1) water scarcity in the dissected plateaus is a direct function of lack of saturation of the aquifers, owing to the rocks being well drained; and (2) abundance in the central valleys is because of their situation in the discharge areas of the basins and also in the regions of maximum irrigation, both of which cause high water levels. Countering these challenges is a very difficult task and needs systematic integrated approaches and public cooperation. Water scarcity in the dissected plateaus can be addressed through construction of several artificial recharge structures at suitable locations for augmentation of the available groundwater resources. In the water-abundant areas in the central valleys, consumptive use of water resources is highly recommended. Springs may be harnessed effectively at higher elevations. More number of dugwells may be constructed in deeply buried pediments, while the areas having NE-trending lineaments and fracture patterns may be looked for greater success of the borewells.

REFERENCES

Naik PK, Awasthi AK, Anand AVSS, Mohan PC (2001) Hydrogeologic framework of the Deccan terrain of the Koyna River basin, India. Hydrogeology Journal 9(3):143-264

Naik PK, Awasthi AK, Mohan PC (2002) Springs in a headwater basin in the Deccan Trap Country of the Western Ghats, India. Hydrogeology Journal 10(5):553-565

Naik PK, Awasthi AK (2003) Groundwater resources assessment of the Koyna River basin, India. Hydrogeology Journal (in press).

Focus on groundwater in Sudan

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Sudan is dependent upon groundwater for its supply of water, both for human consumption and irrigation. Sudan has a unique position in the varied and rich geography in the Muslim and African world. This article deals with the present groundwater resources. The decision where and how much groundwater to pump depends inter alia, on the quality of groundwater and the depth from which it has to be pumped. The further development of groundwater for agriculture and domestic use is one of the priorities to improve the agricultural yield of the country, and the domestic and industrial for water supply situation (groundwater needs little treatment). Other factors that should be considered in planning priorities of water demand (type, distribution, quality), are the availability of alternative resources, the existing development plans, and the sociological conditions and political priorities. The present minimum annual requirements of water for human and animal consumption in the rural areas of Sudan are estimated to be 275 x 10^6 cubic meters (23.2% of this amount is provided from the groundwater). About 1381 x 10^6 cubic meters are estimated to recharge the major basins annually. Only 143 x 10^6 cubic meters of this recharged water is used because of lack of proper policies, technical manpower, inadequacy of knowledge and absence of appropriate research to develop new technologies and approaches. It can be concluded that the groundwater potential of the basins are extremely high. Finally, large quantities of groundwater are available for future development in irrigation and domestic supply.

CONCLUSION

1. Groundwater resource plays a major role in the development of many areas in Sudan. The resources will be used in multi-purpose projects, including: domestic, industrial, irrigation and livestock. The appraisal of groundwater resources is expensive (35 million Sudanese pound per well), and time-consuming procedure if exact quantitive estimates are required.

2. About 1,381 million cubic meters are estimated to recharge the major basins annually. Only 143 million cubic meters of recharged water is abstracted for different purposes because of lack of appropriate and consistent policies for groundwater development, shortage of professional and technical manpower and training facilities.

3. Several projects are now developed for the use of groundwater in irrigation. About 2.1 x 10^9 square meters are planned to be irrigated from groundwater.

4. The continuation of the numerous research projects is essential for proper utilisation of groundwater resources.

5. The data presented in this paper can be considered as nucleus information for executing research and development of groundwater resources; at the same time, they could determine sites that are likely to have a better prospect.

6. Finally, a data bank will be needed to provide all the necessary information for scientific studies as regards water matters.

Isotope studies of a groundwater-flow system in granite, Middle Hungary

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A b s t r a c t : A large-scale research project is going on in Hungary to find the most suitable territory for a low and intermediate level radioactive waste repository. A granite bulk located near Bátaapáti, between the Mecsek Mountains and Szekszárdi Hills seems to be the best geological formation for this purpose. The groundwater-flow system is studied by isotope investigations. The granite rock of Carboniferous age is covered by 30-70 metres thick Holocene and Pleistocene sediments. The sediment is mostly aquitard with several infiltration zones. The peripheral part of the granite body is more fractured than the inner part. The water movement in the compact granite is very slow, about 10^{-9} m/s, but in the fractured granite it can be higher. The properties of the flow system were investigated by isotope measurements of groundwater samples from the boreholes. The δ-values and radiocarbon ages show that Holocene waters appear in the upper and peripheral part of the granite body, and glacial, pre-glacial waters are present in the deeper part of the bulk. Transport model calculations are carried out to determine the flow-paths. If the water flow-paths are out of the inner part of the granite complex then this field is suitable for repository from hydrogeological point of view.

INTRODUCTION

To deposit the radioactive waste is a great challenge in the world. In Hungary a great research project is going on to find the most suitable site for a low and intermediate level radioactive waste repository. A granite complex located near Bátaapáti, between the Mecsek Mountains and Szekszárdi Hills in Middle Hungary seems to be the best geological formation for this purpose. One of the most important questions in the preliminary safety assessment is that how the water moves in the granite rock. The groundwater flow system is studied by isotope examinations (tritium, carbon-14, $\delta^{13}C$, δD, $\delta^{18}O$, dissolved salts, noble gases, etc.).

EXPERIMENTAL

Tritium, radiocarbon, stable isotope ratios were measured in all water samples, and dissolved noble gases in a few samples were analysed. The tritium was determined by helium-3 ingrowth method with a noble gas mass spectrometer (VG 5400). The detection limit of this method is less than 0.005 TU. The accuracy of the measurements is 2-4 % in the range of 1-20 TU (Palcsu *et al.* 2002). Stable isotope ratios (δD and $\delta^{18}O$) of water were measured by a Finnigan Mat delta S, and $\delta^{13}C$ of dissolved inorganic carbon were measured by a McKinney-Nier-type stable isotope ratio mass spectrometers (Hertelendi *et al*. 1987). Dissolved noble gas measurements, mostly helium, were carried out with the above mentioned noble gas mass spectrometer. The radiocarbon activity of the dissolved inorganic carbon was measured by gas proportional counters. The counter-gas was high purity CO_2 gas produced from the sample. The overall precision of the system for modern carbon samples is better than 4 ‰ after a counting period of seven days (Hertelendi *et al*. 1989). The radiocarbon age is calculated according to the Ingerson-Pearson model.

GEOLOGICAL BACKGROUND

The granite body was produced in the Carboniferous. It is covered by 30-70 metres of Holocene and Pleistocene loess sediment. The sediment is partly watertight, but there are zones where infiltration to the deeper area is possible. The peripheral part of the granite is fractured whereas the inside one is unaltered. The flow velocity in the compact granite is very low, about 10^{-9} m/s, but in fractured granite it may be higher. The properties of the flow system were investigated by isotope measurements of groundwater samples from the boreholes drilled down to 350-400 metres into the granite. Fig.1 represents the locations of the boreholes in the area. The water samples arise from different filter depth (see Tab.1). A and B represent monitoring wells very close to the given boreholes or each other. The monitoring wells provide water samples from the first shallow aquifer.

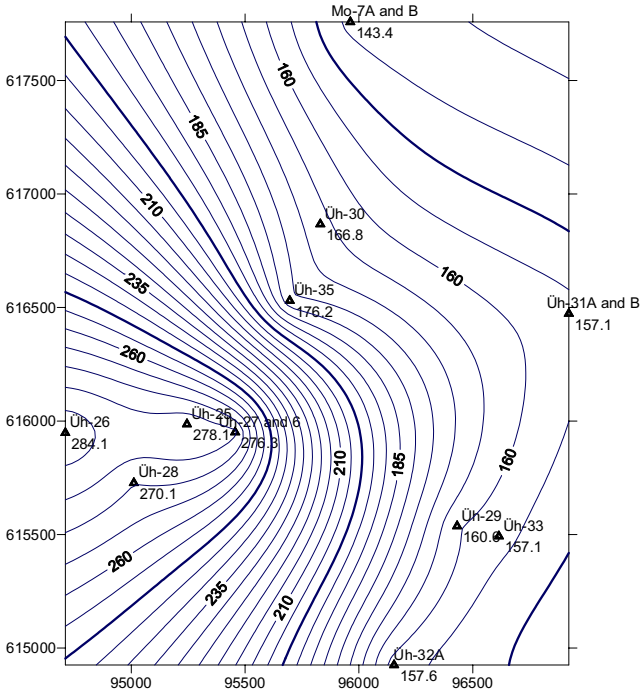

Figure 1. Map of the studied area: altitudes and labels of the boreholes are represented

RESULTS AND DISCUSSION

Two groups of boreholes were distinguished in the data evaluation: boreholes at the top of the hill (Üh-25-26-27-28-6), and boreholes in the valley (Üh-29-30-31AB-32A-33-35 and Mo-7A-7B). In the first group the wells were deep (down to 400 m) with the possibility to sample from 400 m depth, while the wells in the valley were relatively shallow (180-200 m). All samples, mostly in the shallow ones, contained more or less tritium (see Tab.1). It is natural in case of water tables close to the surface, but in the deeper layers it can be the remains of the drilling water. The tritium content decreased with the depth. It can be also seen in Tab.1 that the water became older with increasing depth according to the radiocarbon ages, which increased to 21-22 ka. Two boreholes in the valley (Üh-29 and 30) provided also very old water, the age of the water from 150-160 m in well Üh-30 was the oldest one (38.2 ka).

Table 1. Data of the water samples of the examined boreholes in the research area

Sample Identifier	Date of sampling	Filter (m)	$\delta^{13}C_{PDB}$ (per mil)	^{14}C (pmC)	Radiocarbon age (year)	δD_{SMOW} (per mil)	$\delta^{18}O_{SMOW}$ (per mil)	Tritium (TU)
Üh-25A	14/06/2002	66.8-68.7	-	-	-	-	-	0.040±0.007
Üh-25	06/09/2002	192.5-203.2	-11.9	10.6	12460	-82	-11.39	0.030±0.010
	17/10/2002	249.6-260.0	-12.2	4.8	19170	-93.2	-12.84	-
	04/11/2002	289.8-300.7	-12.9	3.9	21360	-97	-13.23	0.017±0.007
Üh-26A	14/06/2002	62.0-73.0	-	-	-	-	-	0.300±0.060
Üh-26	17/07/2002	211.8-229.0	-10.8	4.1	19500	-97.7	-13.36	0.010±0.008
	01/09/2002	304.2-324.3	-11.6	9.2	13380	-92.1	-12.58	-
	26/08/2002	389.8-400.6	-11.5	3.3	21780	-90	-12.5	0.080±0.020
Üh-27	25/07/2002	242.9-253.5	-13.4	23.0	7000	-74.4	-10.47	0.009±0.006
	02/08/2002	273.7-284.3	-13.9	29.2	5300	-78.7	-11.15	0.032±0.009
	17/08/2002	380.3-391.1	-13.8	10.0	14100	-87	-11.94	-
Üh-28A	24/07/2002	51.4-52.7	-	-	-	-	-	0.050±0.010
Üh-28	05/10/2002	149.2-158.1	-12.7	17.7	8740	-70.7	-10.18	0.032±0.008
	29/09/2002	246.9-271.5	-11.2	3.6	21270	-89.6	-12.4	0.013±0.007
Üh-6	14/06/2002	71.7-79.7	-	-	-	-	-	0.059±0.008
Üh-29	21/08/2002	0.0-5.0	-	-	-	-	-	8.2±0.2
	14/09/2002	54.2-65.7	-14.7	92.9	0	-68.7	-9.86	9.1±0.2
	19/09/2002	85.3-104.8	-12.6	39.9	1920	-79.3	-11.33	-
	08/10/2002	179.2-190.8	-11.4	3.9	20330	-89.6	-12.43	-
Üh-30	06/08/2002	0-19.9	-14.2	78.5	-	-70.2	-9.83	1.5±0.05
	27/08/2002	50.1-78.9	-13.8	55.2	-	-76.6	-10.85	0.130±0.020
	18/09/2002	119.7-130.3	-12.4	6.0	17440	-96.1	-13.28	0.051±0.009
	22/09/2002	148.2-160.3	-12.7	0.5	38210	-99.2	-13.58	-
Üh-31A	22/06/2002	31.8-36.6	-14.7	85.4	0	-70.7	-9.98	5.5±0.2
Üh-31B	30/06/2002	0-18.2	-15.5	100.4	0	-68.1	-9.72	-
	10/07/2002	34.7-40.0	-	-	-	-	-	3.1±0.1
Üh-32A	29/06/2002	26.9-50.0	-13.1	31.9	4100	-78	-10.87	0.080±0.010
Üh-33	15/10/2002	35.6-44.0	-13.7	74.5	0	-69.6	-9.79	0.520±0.020
Üh-35	14/11/2002	30.0-44.2	-	-	-	-	-	0.330±0.020
Mo-7A	17/07/2002	37.5-50.0	-14.8	94.6	-	-	-	5.3±0.2
Mo-7B	19/09/2002	32.6-42.6	-14.5	98.7	-	-	-	5.9±0.1

The isotope ratios of deuterium and oxygen became more depleted with increasing depth (-70‰ to -99‰, and -10‰ to -14‰, respectively). This implied that water in deeper layer infiltrated under colder climate (except only the Üh-26). The $\delta^{13}C$ showed an inverse behaviour: the δ-values of carbon isotopes became less depleted with increasing depth (-14‰ to -11‰). It can be explained with the dissolution of hydro-carbonates from the host rock containing $\delta^{13}C$ values close to zero. This fact also confirms that the water samples from the deeper region were very old. Üh-26 borehole also contains very old water, but the changes of the isotope ratios showed an opposite trend, which needs an explanation. The radiocarbon ages as well as the decrease of hydrogen and oxygen isotope ratios with increasing depth allow us to suppose that the water in the deepest layer infiltrated before the Holocene. In three cases it was possible to take noble gas sample. The samples were taken into copper tube sampler. Table 2 shows the helium concentration and isotope ratio ($^3He/^4He=R$ divided by the atmospheric ratio R_a) data of the samples, which came from the deepest water layer. These helium data are correlated with the radiocarbon ages: the oldest water (Üh30 with38.2ka) contained the most helium, while the less helium was in the water sample from the shallow borehole (Üh-35, filtered between 30 and 44.2 m).

Holocene water can be found in the upper and peripheral part of the granite body, but in the deeper part of the bulk pre-glacial waters appear. Transport model calculations are in progress to determine the flow-paths. On the basis of isotope data we can assume that the water doesn't flow in the inner part of the granite bulk and so the field is suitable for repository from hydrogeological point of view.

Table 2. Helium data of water samples of three boreholes from the deepest layer

Sample Identifier	R/R_a	Helium ($ccSTP_{He}/g_{H2O}$)
Üh-27	0.026	$5.0 \cdot 10^{-6}$
Üh-30	0.014	$3.7 \cdot 10^{-5}$
Üh-35	0.548	$8.7 \cdot 10^{-7}$

REFERENCES

Palcsu L, Molnár M, Szántó Zs, Svingor É, Futó I (2002) Metal container instead of glass bulb in tritium measurement by helium-3 ingrowth method. Fusion Science and Technology 41, 3, 2:532-535

Hertelendi E, Gál J, Paál A, Fekete S, Györffi M, Gál I, Kertész Zs, Nagy S (1987) Stable isotope mass spectrometer. Fourth Working Meeting Isotopes in Nature. In: Wand U, Strauch G (eds) Akademie der Wissenschaften der DDR Zentralinstitut für Isotopen und Strahlenforschung, Leipzig 1:323-328

Hertelendi E, Csongor É, Záborszky L, Molnár J, Gál J, Györffi M, Nagy S (1989) A counter system for high-precision 14C dating. Radiocarbon 31:399-406

Groundwater responses to recharge and human-induced stresses in the Trifilia karst aquifer, Greece

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A b s t r a c t : The aim of the paper is the description and interpretation of the hydrogeological conditions in the SW Trifilia coastal karst aquifer. Hydrographs of water table and electric conductivity daily responses plotted against daily rainfall indicate that the water table is settled within the fluctuation limits between the dry and wet season while the electric conductivity remains constant. The pumpings of the last 8 years had no impact on the low salinity groundwater of the karst aquifer, since the annual recharge remains higher than the annual water extractions.

INTRODUCTION

The study area is located in the southwestern part of Peloponnesus, in the Trifilia province of Greece. The mean annual temperature is 16.3 ^{o}C while the mean annual precipitation is 749 mm (Filiatra station). Trifilia is an agricultural area with increased demands of irrigation water, covered mainly by the exploitation of the karst aquifer.

The bedrock of the research area belongs to the Tripolis series and is composed of a thick sequence of Eocene limestones and dolomitic limestones overlain by an Oligocene flysch (ESSO-HELLENIC 1980). Pleistocene and Holocene deposits unconformably overlie all of these sediments (Fig.1).

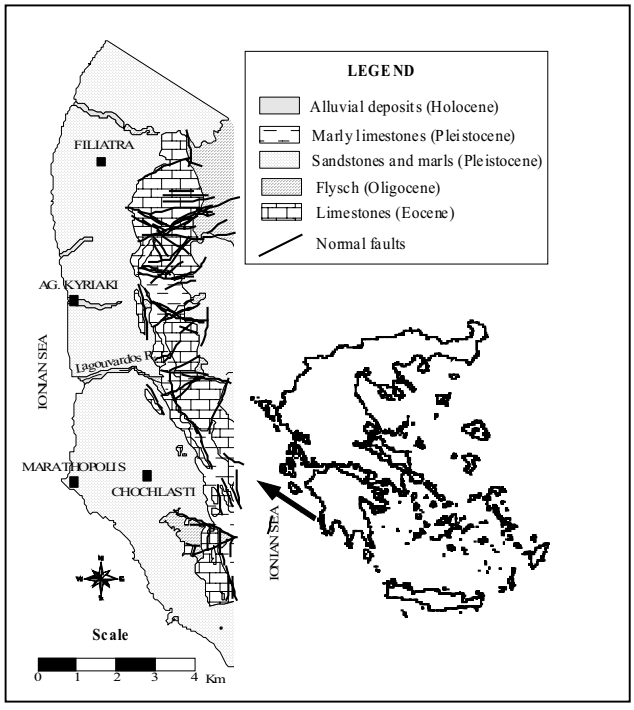

Figure 1. Geological map of the research area (ESSO-HELLENIC 1980)

The karst terrain of Trifilia can be considered as an *eogenetic karst*, a term proposed by Mylroie and Vacher (1999) to describe a system developed in young (Cenozoic) limestones where post-depositional alteration has taken place in the realm of actively circulating groundwater. Karstification produces a dual-porosity aquifer in which dissolution-widened fractures are typically superimposed on a high-porosity matrix (Contractor and Jenson 2000). The eogenetic karst model suggests that most of the flow in the phreatic zone of young limestone aquifers is probably Darcian (Jocson *et al.* 2002).

HYDROGEOLOGY

A dense system of faults and fractures intersects the carbonate sediments of Trifilia in NNW-SSE and NE-SW directions (Fig.1) and constitutes the main drainage network of the karst aquifer (Fig.2). The hydraulic gradient is extremely low in the northern and southern part of the aquifer (0.2‰ and 0.3‰ respectively) with a relatively increased value of 1.5‰ in the central part of the aquifer. The low values of hydraulic gradient can be attributed to a very high hydraulic conductivity and transmissivity of the karst aquifer (100 m/d and 7000 m^2/d respectively).

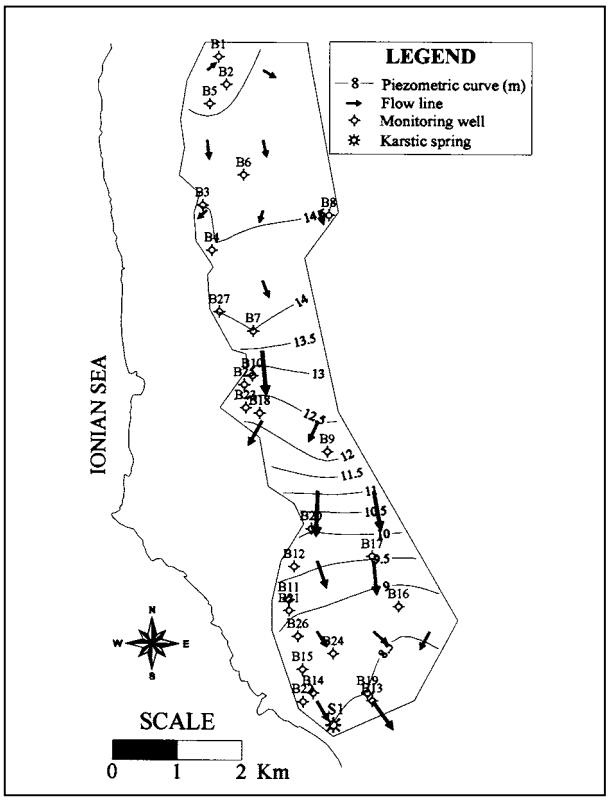

Figure 2. Piezometric map of the karst aquifer (October 2002)

Aquifer responses to recharge

Hydrographs of the aquifer were obtained after installing automatic multi-parameter probes at B2 and B23 piezometers (Fig.2), five meter below the water table. The system configured for continuous recordings of the water table and electric conductivity with a half-hour step during the period May 2001 - February 2003. The resulted hydrograph (Fig.3) shows the water table response (averaged in daily values) to precipitation, which is normally fluctuated between the wet and dry season of the hydrological year. On the contrary, electric conductivity remains

relatively constant in spite of the pumpings during the summer period.

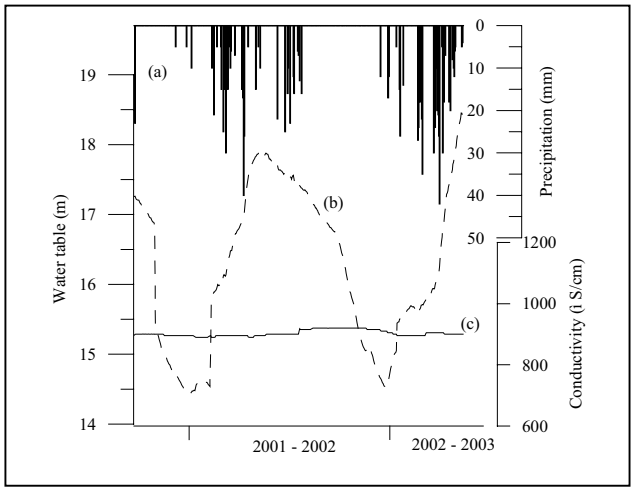

Figure 3. Composite plot of precipitation (a), water table (b) and electric conductivity (c) in the B2 piezometer

The exploitation of the karst aquifer started at the early 80's with a small number of production wells until 1995. The 60% of the existing boreholes were constructed during the period 1996-98, exclusively for irrigation purposes (Fig.4). The human-induced stresses by the pumpings to the water resources of the Trifilia karst aquifer were examined in B1 and B22 boreholes by comparing the water table data of the 1990-92 (Sampatakakis, unpublished data) with the 1998-2003 period (Fig.4).

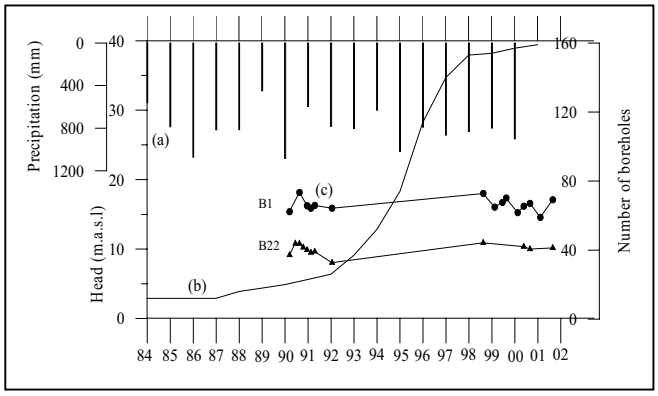

Figure 4. Comparative plot between annual precipitation (a), annual increase of productive wells (b) and water table of the B1 and B22 boreholes (c)

It is clearly shown that the increase of the number of the productive wells in the study area had no influence on the groundwater level, since it remains constant through the last two decades.

Groundwater balance

A simplified equation of the hydrologic balance is given by the equation:

$$P = R + E + I$$

where P is the mean annual precipitation, R is the mean annual surface runoff, E is the mean annual evapotranspiration and I is the mean annual infiltration. Assuming that the runoff in the karst terrain of Trifilia is negligible, the difference between precipitation and evapotranspiration is the quantity of rainwater that infiltrates directly the aquifer. This parameter was computed based on the procedures described by Thornthwaite and Mather (1955).

Following Jocson's *et al.* (2002) concepts and terminology for eogenetic karst aquifers, the infiltrated as above rainwater corresponds to the *vadose percolation* plus *vadose fast* flow. The *net input* in the case of Trifilia karst aquifer equals to this quantity plus the annual volume of the Lagouvardos River that infiltrates the aquifer (I_L) through the streambed (Panagopoulos and Lambrakis 2001). The *output* from the aquifer is the sum of *seep flow* (Q_I), *spring flow* (Q_S) and *pumped flow* (Q_P). The spring flow corresponds to the discharge of the S1 karstic spring while seep flow is estimated from the equation of the groundwater balance, which the final expression can be written as follow:

$$\text{Input} = \text{Output} \pm \Delta S \text{ or}$$
$$I + I_L = Q_I + Q_S + Q_P \pm \Delta S$$

where ΔS is the aquifer storage, which adjust to accommodate for net balance between Input and Output. The aquifer storage equals to A*dh*S (Kallergis 2001), where A is the aquifer area, dh is the water level change between the dry and wet season and S is the storativity (specific yield) estimated by pumping tests. The mean groundwater balance of the karst aquifer is given in Tab.1. From the above table results that the annual recharge of the aquifer is much higher than the annual water extractions. This fact explains the lack of water table fluctuations during the last 8 years, although important quantities of groundwater are pumped out (6.9×10^6 m^3/year).

Table 1. Mean annual groundwater balance of Trifilia karstic aquifer for the period 1998 – 2002 (x 106 m3)

I	10.9
I_L	2.5
Q_I	6.3
Q_S	0.2
Q_P	6.9
ΔS	12.8

CONCLUSIONS

A dense network of faults and fractures intersects the carbonate sediments of Trifilia, forming an eogenetic karst aquifer with a high dual porosity. The hydraulic gradient is very low and the aquifer is very high permeable. The aquifer is highly recharged from rainwater infiltration and surface water percolation, which prevent the water shortage in spite of the increased water extractions of the last years.

REFERENCES

Contractor DN, Jenson JW (2000) Simulated effect of vadose infiltration on water levels in the Northern Guam Lens Aquifer. J Hydrol 229:232-254

ESSO-HELLENIC (1980) Geological map of Greece, Filiatra sheet, I.G.M.E., Athens

Jockson JMU, Jenson JW, Contractor DN (2002) Recharge and aquifer response: Northern Guam Lens Aquifer, Guam, Mariana Islands. J Hydrol 260:231-254

Kallergis G (2001) Applied-Environmental Hydrogeology, vol. 3, 2nd edition. Technical Chamber, Greece, 431 pp

Mylroie JE, Vacher HL (1999) A conceptual view of carbonate island karst. In: Palmer AN, Palmer MV, Sasowsky ID (eds) Karst Modeling Symposium, Charlottesville, VA:48-58

Panagopoulos GP, Lambrakis NJ (2001) Investigation of the quality of groundwater of SW Trifilia karstic aquifer in respect with the hydrogeological conditions of the area. Bulletin of Geological Society of Greece, vol. XXXIV/5, pp 1885-1892, 2001. Proceedings of the 9th International Congress, Athens, September 2001 (In Greek)

Water storage and recovery project for sustainable groundwater resources in fractured hard-rock aquifer

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A b s t r a c t : Water storage and recovery program was carried out to provide the construction water for the Arizona Department of Transportation (ADOT) State Route (SR) 260 highway upgrading project between Payson and Heber in Gila County, Arizona. The primary objective of the water supply study was to identify viable groundwater source(s) in fractured granitic rock that could meet the water demand of the project (about 300 gallons per minute (gpm)), while having minimal impact on natural creeks, springs, existing wells, and water-dependent resources. Potential Water Storage and Recovery program at the Site was evaluated using the following steps: Geological and Hydrological Evaluation; Well Drilling and Geophysical Investigations; Analysis of Drilling and Geophysical Data; Aquifer Testing; Groundwater Flow Modeling; Analysis of Aquifer Potential and Development of Recharge Model. A groundwater flow model based on discrete fracture flow predicted that the water levels in the well field without recharge would decline significantly during the life of the project and potentially impact the environment. Surface water from nearby Tonto Creek was evaluated as a potential source for artificial groundwater recharge. The average annual flow in Tonto Creek was analyzed to establish the threshold criteria for surface water withdrawal during the high flow season. The water samples were collected from Tonto Creek exceeded the AWQS (Aquifer Water Quality Standards) for turbidity and total coliforms. Because of these AWQS exceedances, a water treatment plant was constructed to treat water from Tonto Creek prior to injecting water into the well field aquifer. The construction of SR 260 was initiated in 2001 and is currently progressing with an adequate supply of construction water from the hard rock aquifer with the help of recharge from surface water. Recent monitoring data clearly demonstrates the success of artificial recharge in reducing the impact of withdrawal of ground water.

INTRODUCTION

A groundwater resource evaluation study was carried out for the Arizona Department of Transportation (ADOT) in cooperation with the US Forest Service (USFS) for the State Route (SR) 260 highway upgrading project between Payson and Heber in Gila County, Arizona. The primary objectives of the study were to identify and develop viable groundwater sources that could meet the construction water demand of the project, while having minimal impact on the environment, existing groundwater users, and water-dependent resources. It was estimated that 257.5 million gallons (about 790 acre-feet) of water would be needed during the 10 years of roadway construction. The peak water demand was established to be 225 gallons per minute (gpm). The dominant rock along the project corridor is Precambrian granite, locally referred to as the Payson granite. Wells completed in the granite generally yield less than 50 gpm. The groundwater resource evaluation was performed in phases, starting with a hydrogeological evaluation of the highway corridor and surrounding area, and culminating with exploration, development and assessment of a well field. Groundwater flow in a fractured crystalline rock like the Payson Granite occurs mainly through the fractures within the rock mass, and is controlled by the geometry and hydraulic parameters of the fractures. A discrete fracture flow model predicted that detrimental impacts could result from long-term pumping of the well field. As a result, seasonal surface recharge from a local creek to the well field was recommended to mitigate the potential impacts. The artificial recharge of surface water will assist in reducing the demands on the well field, and potential impacts to the environment will be minimized. Furthermore, the post-construction groundwater condition will be returned to a pre-construction condition.

HYDROLOGICAL EVALUATION

The hydrogeologic evaluation included a compilation of existing geologic mapping and a review of available hydrologic data for five target sites along the project corridor. Hydrogeologic maps of the sites were compiled by plotting all existing wells, springs and streams located within at least a 1½- mile radius of the target sites. In conjunction with the preparation of the site maps, a photolineament analysis of the project area was performed using available aerial photographs at scales of 1:12,000 and 1:24,000. 1:12,000 and 1:24,000. A Landsat lineament map of Arizona was also reviewed for information on the orientation of major structural features in the project area. A field reconnaissance of the target sites was performed to verify the location of wells, springs and major structures in order to select exploration well locations. Based on the hydrogeologic evaluation, three target sites were selected for exploratory wells. Out of these three sites, only one site (the RV site) was selected for detailed investigation. Five exploratory wells were drilled at the RV site and short-term (8-hour) aquifer tests were performed.

GEOPHYSICAL INVESTIGATION

Acoustic televiewer, electrical guard resistivity, caliper, natural gamma, gamma density, neutron porosity and sonic VDL logs were completed at Well R-1 to evaluate their effectiveness in characterizing the fracture system and hydrogeologic conditions in the well field. Based on this evaluation, selected geophysical logs were performed in the other wells at the RV site. The correlation between different geophysical logs was used to establish the location and permeability of the major fracture zones within the aquifer. Geometrical and hydraulic properties of the fractures were interpreted from the geophysical logs. This provided the basis for developing the discrete fracture flow model, which was used to simulate and predict the future performance of the well field aquifer.

AQUIFER TESTS

Several aquifer tests were performed at the RV well field to characterize the hydraulic properties and long term performance of the aquifer. Well R-2 was pumped for a period of 24 hours and drawdown and recovery measurements were recorded in Well R-2 and surrounding wells. Well R-4 was pumped for a period of 7 days, and drawdown and recovery measurements were recorded for all the wells at the RV site.

Wells R-1, R-2, R-3, and R-4 were all pumped for a period of 38 days, and drawdown and recovery measurements were recorded at all of the wells at the RV site. Six observation wells were drilled to monitor the water levels during the pump tests. In addition, the flow rate at two nearby springs, Mud Spring and

Unnamed Spring, and Green Valley Creek were measured and recorded. At the end of the test, the drawdowns at Wells R-2 and R-4 were about 60 and 70 feet, respectively, and the drawdowns at Wells R-1 and R-3 were 120 and 200 feet respectively. The drawdown in the observation wells ranged from less than one foot at Well R-5 to almost 34 feet at Well O-1. The anisotropy observed during the 24 hour test was also apparent in the 38 day test.

DISCRETE FRACTURE FLOW MODEL

The RV site seems to be characterized by two different statistical homogeneous regions. Due to the presence of a complex fracture network pattern and the observation that the flow is practically restricted to the major fractures within the aquifer, the equivalent continuum media assumption does not adequately describe the flow behavior at this site. Ground water flow within the aquifer was found to be highly anisotropic. Therefore, a flow model based on the discrete fracture flow approach Panda and Kulatilake (1999) was used to address this anisotropy. The generation of a conceptual joint network and simulation of pump tests were developed by Wang *et al.* (2000). The 24 hour pump test of Well R-2 and the 7 day pump test of Well R-4 were used to calibrate the transmissivity (T) and storativity (S) values for different zones in the discrete fracture network. The simulations were then validated with the data generated from the 38-day pump test using the calibrated T and S values.

WATER STORAGE AND RECOVERY SYSTEMS

The flow model predicted that water level in the aquifer would decline by more than 100 feet over the life of the project. Decline in the water levels would impact discharge from nearby springs and flow in Green Valley Creek. In order to mitigate the impacts, it was recommended that surface water from Tonto Creek, located about 8 miles east of the well field, could be used to recharge the RV site well field. Withdrawal of water from Tonto Creek would be limited to periods of high flow in order to minimize impacts to the creek system. A very small amount (less than 1%) of surface flow would be needed to recharge the RV well field. Two additional injection wells were installed to recharge the surface water in to the underground storage.

CONCLUSION

The primary objectives of the groundwater resource evaluation were to identify and develop viable groundwater resources along the highway corridor that could meet the construction water demand of the project, while having minimal impact on the environment, existing water users, and water dependent resources. Borehole geophysical logging was performed to characterize aquifer materials and the fracture network. The groundwater flow in the RV well field is dominated by flow through fractures. Hence, a discrete fracture flow model was developed. The computer model predicted that the water levels in the well field would decline by over 100 feet during the life of the project. The artificial recharge of surface water into the groundwater was found not only to reduce the demand of the groundwater resources in the well field but also mitigate the potential environmental impact to the existing wells, springs and creek.

REFERENCES

Panda BB, Kulatilake PHSW (1999) Influence of joint geometry and transmissivity on jointed rock hydraulics, ASCE, Journal of Engineering Mechanics 125(1):41-50

Wang M, Kulatilake PHSW, Panda BB (2000) Discrete fracture fluid flow simulation of pumping tests in fractured rock mas s. Pacific Rocks 2000:831-839

Planning of conjunctive use of surface and ground water in the Ghataprabha irrigation project through numerical groundwater model

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The isolated development of surface water, without systematic development of groundwater resources within the command area will result in undesirable consequences like water logging and soil salinity affecting sustainable production. Keeping in view of the alarming nature of the problem, the National Water Policy (1987) rightly advocated the integrated development of both surface and groundwater and their conjunctive use in the command as an effective measure for combating the menace.

Conjunctive use of surface and groundwater not only provide the best solution for beneficial use of water resources but also provide additional water for increasing the intensity of irrigation and availability of more water in the tail end reaches of canal. Ghataprabha command in Karnataka State is one of the commands where conjunctive use studies were taken up.

The total area taken up for study is 10370 sq.km bounded by the north latitude 15°45' and 16°40' and east longitude 74°15' and 76°00'. The canal command area is served by both left bank and right bank canal systems. The net irrigated area in the left bank and right bank canals are 1,61,871 ha and 1,55,559 ha respectively.

The major crops grown in the area are Paddy, Sugarcane, Ragi, Bajra, Jowar, Maize, Pulses, Groundnut, Cotton and Oil Seeds. There are two major crop-growing seasons namely ***khariff*** which starts from July and ends in October and ***rabi*** from November to February/March.

In the non-command area, the khariff season depends on rainfall and minor irrigation structures like tanks and wells while in rabi season, it is predominantly well irrigation. In the canal command area, irrigation water is generally given through canals by June end or July first week.

In the canal command, generally, the proposed cropping pattern to be followed in the ensuing khariff and rabi seasons are notified in advance. The cropping pattern followed in the command area is 40% kharif, 40% rabi and 20% biseasonal.

Geologically, the area is underlain by rocks of Archaean crystallines to recent alluvium. While granites, gneisses and schsits occur in pockets, the Kaladgi formations are seen predominantly in the southern and eastern parts of the study area and Deccan traps in the northern part. Alluvium occurs within the major river and stream course. The sub surface geology of the area, the distribution of aquifer systems and their geometry indicates that generally two distinct aquifer system is present in the area.

Groundwater level changes occur due to seasonal variations in rainfall, seepage from canals and return flow from irrigated fields which affect the recharge and discharge components of the groundwater regime. Water levels rise immediately after the release of canal water, remains stabilized during the period of canal operations and thereafter there is a fall especially in the canal command. In the middle reaches of the canal, the water levels reach a peak by November and decline starts by April when the canal is closed, while in tail end areas, the peak is reached by January and decline starts by March (Figs.1a,1b&1c). It is possible that due to insufficient canal water for irrigation, the wells are put to use during the period, which results in decline of the water table.

Water logging conditions occur due to shallow water level conditions, which is due to poor drainage and due to excess irrigation. During the year 1993-94, canal water was released in the first week of July 1993, water logging conditions were observed over an area of 143 sq.kms, which increased to 344 sq.km by August 1993 and to 580 sq.kms by November, 1993. This suggests the build up of the water levels.

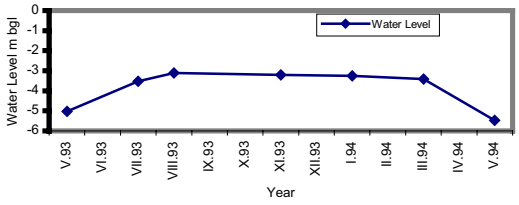

Figure 1(a). Hydrograph of key observation well at Arabhavi, Gokak taluk (Upper reaches) in Ghataprabha command area

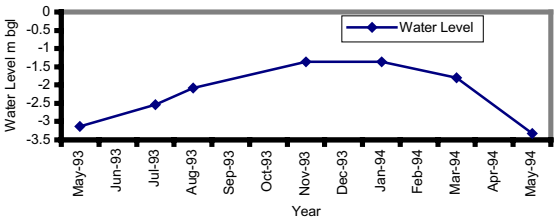

Figure 1(b). Hydrograph of key observation well at Yadahalli, Mudhol taluk (Middle reaches) in Ghataprabha command area

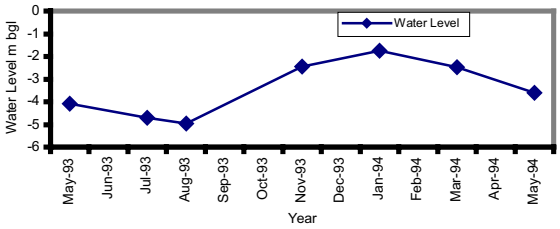

Figure 1(c). Hydrograph of key observation well at Badagundi, Bilgi taluk (Tail End) in Ghataprabha command area

A numerical model has been developed for the area using USGS MODFLOW and the data generated from the field investigations. The model is calibrated using historical water level data. The hydrograph of observed water levels and computed water levels are shown in fig.2. The calibrated model is utilized for generating different development options/scenarios. Five scenarios, depicting various improved changes on the aquifer system were developed (Fig.3).

From the model runs, it is observed that general water logging conditions exists in the upper reaches. It can be said that with a rise in the tempo of development, there will be reduction in the water logged area over the years.

Conjunctive use mechanism vis-à-vis the water demand computed for various cropping intensities for the two commands have shown that for the left bank canal command, a cropping intensity of 200% seems to be feasible. Higher cropping intensity of 240% is not practical because of increased groundwater utilization which may create over exploitation conditions.

A conjunctive use plan has been suggested for the command area which can be executed in stages. The conjunctive use plan envisages construction of 20500 borewells in the both canal commands with an investment of Rs. 400 million, irrigating additional 56000ha. To achieve maximum benefit under the conjunctive use plan the water user societies have been suggested who will operate and maintain the borewell constructed under the scheme.

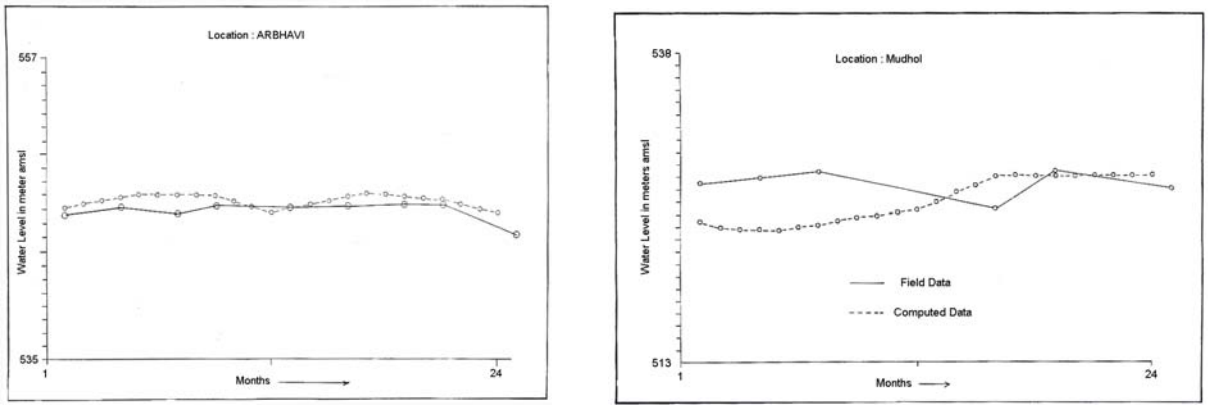

Figure 2. Ghataprabha conjunctive use studies calibration

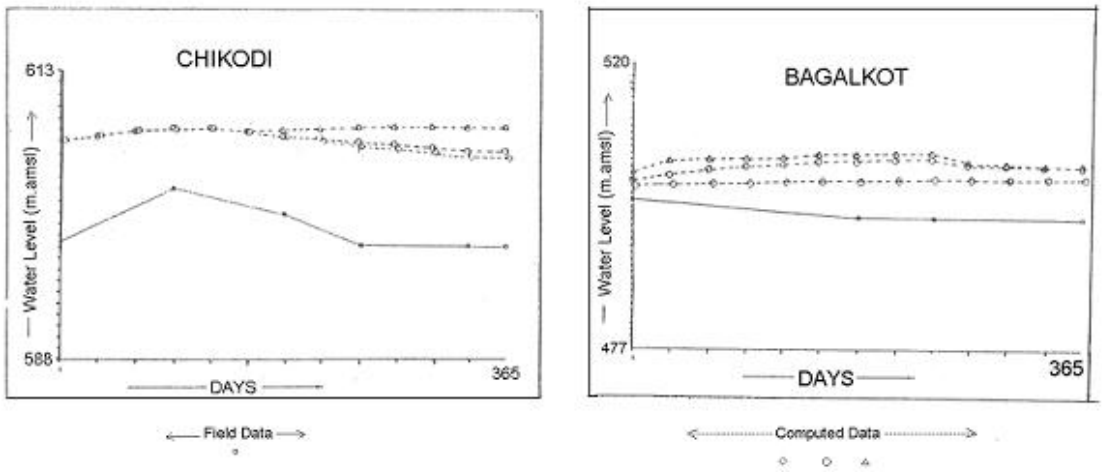

Figure 3. Ghataprabha conjunctive use scenarios (Period 1992-93)

Modelling the groundwater flow over four years in a small alpine crystalline headwater catchment

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A b s t r a c t : A new subsurface flow generation concept is developed to cope with the difficulties of underground hydraulic parameter identification. Assuming that large infiltration corresponds to important groundwater flow, and vice versa, time and space variable hydraulic conductivity and storativity values must be calibrated. The analysis is conducted at the headwater catchment Höhenhansl (0.4 km²) and a period of four years is analysed and simulated (10/95 – 09/99). It is assumed from the data analysis that the water flow in approximately the first metre of soil is primarily vertical. The water fluxes simulated under grassland and forest with the van Genuchten – Mualem approach are introduced in the groundwater model. These daily spatially distributed values are used to determine the hydraulic conductivity and storativity time series over the four years.

INTRODUCTION

In mountainous regions system structure and process dynamics are characterised by high heterogeneity. In this respect, one of the most important problems to apply distributed physically based models in these environments is the underground hydraulic parameter identification (Beven 2000).

Although less is known about the parameter distribution in space, much progress has been made concerning the subsurface flow process understanding. As described by Whipkey and Kirkby (1980) "*the difference between saturated subsurface soil flow and groundwater flow is that percolation times, hydraulic gradients and permeabilities all tend to be lower for the latter. If there is appreciable groundwater flow therefore, it tends to behave more like unsaturated than saturated throughflow in terms of its response times".*

This is an important piece of information because it permits to relate subsurface flow and infiltration dynamics. In this work it is assumed that large infiltration corresponds to an important subsurface flow and vice versa. The subsurface flow response times to infiltration are quite variable depending on the depth of the unsaturated zone, its hydraulic conductivity and the actual water content. Although they are generally unknown in nature, in this study the different response times shall be reproduced through the time variable parameterisation. This means that the depth integrated hydraulic conductivity and storativity are varying (1) in time in response to the deep percolation dynamics and (2) in space depending primarily on the land use cover.

METHODOLOGY

Area description and hydrological behaviour

The small headwater catchment area of Höhenhansl (0.39 km², mean altitude 966 m asl) is located in the low mountain region of Eastern Styria (Austria). The mean slope inclination is 17° but the maximum value is about 30°. Geology is characterized by crystalline schists and gneiss covered by a sandy-loamy weathered layer. Geophysical investigations revealed 3 different aquifer types: weathered zone, loose zone and fractured zone (Harum *et al*. 2000). The vegetation is dominated by forest (about 2/3 of the total surface) with few parts of grassland and little anthropogenic impact. This watershed was a hydrological test site within the frame of the European project AGREAUALP (Agri-Environmental Measures and Water Quality in Mountain Catchments) and is equipped with a dense hydrological network: 2 meteorological stations, 2 stations with suction cups, tensiometers and TDR-probes in different depths and gauging stations at the cathment outlet and at the main spring.

Interpretation of the data collected at the Höhenhansl lysimeter stations and at the gauging stations indicates a highly variable underground flow dynamic in time and in vertical distribution. The spring discharge assumed to be representative for the water release from deep stores located in the loose material and in the hard rock displays a great variability over the period between 10/95 – 09/99. During humid phase, the layer between the soil surface and the stores is supposed to be saturated and consequently (a) the hydraulic head rises in the fractured aquifer and leads to a notable discharge increase, and (b) by pressure wave propagation, the discharge "immediately" reacts to each rain event. As the saturation deficit augments, (a) the hydraulic head and the related discharge decrease, and (b) the discharge is no longer connected to the hydraulic input signals. Therefore the spring hydrographs display a "flat" pattern without peaks. For the entire catchment, the underground flow generation is even more complex. In addition to the deep store component a lateral flow component in 1.20 m depth at the forest station is deduced from the collected data.

The hydraulic behavior described above combines unsaturated and saturated flow in various layers. To numerically reproduce this complex subsurface three dimensional flow generation it would be necessary to know geological formations and hydraulic characteristics. However, this is not the case for the Höhenhansl catchment and for most (if not all) other watersheds. Thus, the three dimensional modelling concept (fully saturated-unsaturated, coupled subsurface – surface water modelling) is not retained in this study.

Concept development

The alternative developed in this paper focuses on saturated subsurface flow generation in a two-dimensional approach, i.e., subsurface flow is simulated without relation to its vertical origin in a depth integrated model using only one saturated layer. This means that the system structure (and behaviour) conceptualisation increases by reducing the complex vertical distribution of hydraulic conductivity and storativity parameters. In this study it is assumed that the 2-dimensional vertical integrated parameter values can be well estimated when daily "deep percolation" values are known, i.e., the lateral subsurface flow behavior is directly related to the "deep percolation" dynamic. As a result values of aquifer hydraulic conductivity and storativity are varying in time and space in relation to the deep percolation dynamics.

The concept for saturated subsurface flow process generation developed in this study is based on two assumptions:

Assumption 1. The top underground zone has a high hydraulic conductivity and a high storativity relative to the deep store(s) hydraulic conductivity and storativity, i.e., the material hydraulic properties display an important contrast with depth and the highest value is found at the top aquifer, the lowest at the basis.

Assumption 2. A "threshold depth" exists over which infiltrated water movement is considered to be only vertical and

under which water movement may be vertical and/or lateral. The threshold is fixed to 1.20 m under forest with respect to the data analyses made at this station. Furthermore, this value is kept constant for the total catchment area, i.e., the corresponding soil horizon is assumed to cover the entire Höhenhansl catchment. It should be noted that deep percolation as used in this work is defined as the water amount that reaches the threshold depth, i.e. water that can not be removed vertically to the soil surface.

RESULTS

Since the aim of this study is to test a new method to simulate saturated subsurface flow, hydrological processes taking place at the soil surface - atmosphere interface are simplified. Overland flow amounts measured during four years at the station forest are kept constant in space for all the forest areas, whereas for grassland areas, values from the grassland station are applied. To calculate daily evapotranspiration amount a soil water budget scheme is applied using for each land use - soil unit a soil water capacity estimated over the root depth. Applying this method on a daily basis, it is found that the deep percolation amount under forest is not sensitive to the soil characteristics whereas for grassland minor differences appear. For simplification purposes only two contrasted deep percolation time series are retained: the first one for the grassland areas with a total amount of about 1700 mm, the second one for forest areas with a total amount of about 1000 mm.

The vertical water movement between the root and the threshold depth is simulated using Hydrus 2-D Simunek *et al*., (1996). Simulations are validated at the station scale using the daily measured pressure head values at 0.70 m, 1.05 m under grassland and only at 1.20 m under forest. The simulations are considered of good quality for the grassland station and of average quality for the forest station.

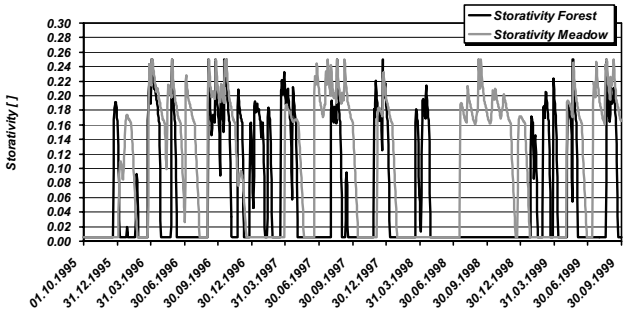

Figure 1. Calculated storativity time series for grassland and forest

The results for the hydraulic parameters calibration are obtained by using the parameters time series. The calibration quality is analysed especially by comparison between the model results and the spring outflow that is only groundwater whereas the catchment discharge encompass also an overland flow part. The final retained parameter range is 1.0e-05 m/s to 2.0e-06 m/s for the hydraulic conductivity and 25e-02 to 5e-03 for the storativity. The calculated storativity time series for forest and grassland are presented on fig.1. The differences between the forest and grassland times series are due to the differences in the deep percolation dynamic under both land use systems. It is also to note that the two conductivity time series display nearly the same pattern.

The simulated discharges using parameter time series and the measured daily discharge from the total catchment and the spring are presented on fig.2. For the first two years the simulations are of poor quality. The high discharge values are not well reproduced with the method tested in this study. This could be a bias introduced by the overland flow and evapotranspiration processes estimation, i.e. the water amount that is allowed to reach the threshold depth is underestimated and the simulated discharge cannot rise like it is the case for the spring and the total catchment. It is also to recognise on fig.2 that the simulated flow amount between March 1997 and September 1997 is too high especially by comparison to the catchment outflow. On the other hand, simulations for the last two years are of good quality for both systems. The few important recession patterns are well fitted for the catchment hydrograph. Furthermore, the spring discharge pattern and amount is mostly well reproduced for the last two years. All in all, it can be said that the method developed in this study presents encouraging results.

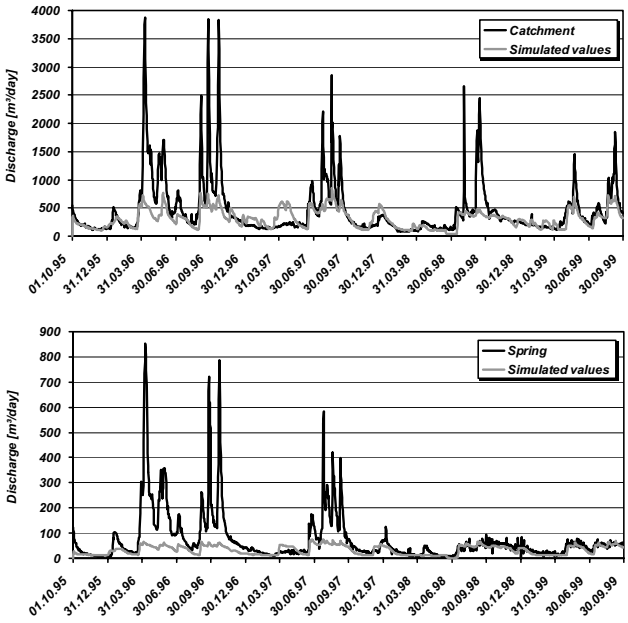

Figure 2. Underground water flow simulations for the Höhenhansl catchment and the main spring using time variable hydraulic conductivity (ranging from 1.0e-05 to 2.0e-06 m/s) and storativity values (ranging from 25e-02 to 5e-03)

REFERENCES

Beven K (2000) Rainfall – Runoff Modelling – The primer. J Wiley & Sons, LTD

Harum T, Kupfersberger H, Poltnig W, Reichl P, Reinsdorff S, Rock G, Ruch CA, Strobl E, Winkler G, Fruhwirth RK, Maier A, Morawetz R, Rieger R, Schön J, Fuchs K, Hofrichter J, Kleb U (2000) „Eros“ Erfassung von Fließprozessen zur hydrogeologischen Bewertung von klüftigen Festgesteinen. Unveröffentlichter Bericht der Joanneum Research GmbH, Graz

Simunek J, Sejna M, Genuchten MTh van (1996) HYDRUS 2D. Simulating water flow and solute transport in two-dimentional variably saturated media. Version 1. International Ground Water Modeling Center. Colorado School of Mines, Golden, CO 80401, USA

Whipkey M, Kirkby M (1980) Flow within the soil. In: Kirkby M. (ed.). Hillslope Hydrology, Wiley J, Chichester, 121-144

Surface-ground water interactions in an upland fractured aquifer system: implications for the role of groundwater in streamflow generation

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A b s t r a c t : The role of groundwater in streamflow generation has traditionally been assumed to be of minor importance in upland catchments. The Plynlimon catchment of Wales is underlain by Ordovician/Silurian rocks which contain significant amounts of groundwater present in a complex fracture network. Fracturing is most intense in the shallow system (down to ca. 10 m), whilst deeper groundwaters occur in discrete fractures. Groundwater samples, collected from sealed boreholes drilled to specific depths show that there is a strong chemical stratification: shallow groundwaters (down to 10 m) are acidic (pH ca. 5) and oxidising, whilst deeper groundwaters are alkaline (pH 9-10) and reducing. CFC data indicate significant increases in age with depth. Seasonal variations in stable isotopes are inconsistent with CFC age but can be reconciled by postulating mixing of older, deeper groundwater with more recent recharge in the shallow system. Intensive sampling during a storm event has shown that the peak stream hydrograph is dominated by older water and a combination of natural chemical tracers and physical measurements indicate that rapid recharge occurs to the shallow fracture system which displaces a well mixed groundwater to the streams.

INTRODUCTION

The Plynlimon upland catchment of Wales (Fig.1) is underlain by shales, mudstones and greywackes of Ordovician/Silurian age. The bedrock in the catchment was traditionally considered to be impermeable and the role of groundwater in streamflow generation was, therefore, considered to be negligible. Much of the catchment is forested and covered with thin acidic soil. The hydrological response of the streams is typical of upland catchments displaying a rapid, flashy response to rainfall events with chemistry changing from more alkaline at baseflow to more acidic during storm events.

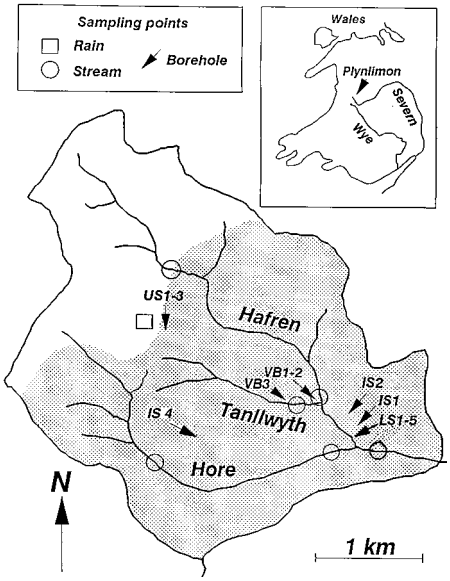

Figure 1. Location of the Plynlimon catchment in Wales. Detailed study site close to LS1-5 on map

The changes in chemistry with flow are inconsistent with traditional models of stream flow generation derived from acidic soils and recent work has highlighted the fact that groundwater is present throughout the catchment (Neal *et al*. 1997; Shand *et al*. 1997).

Fracturing is most intense in the shallow system (ca. 1 m), but extending down to at least 10 m, as a consequence of intense weathering, probably related to periglaciation following the last ice age. Deeper groundwaters are present down to at least 50 m depth, but these tend to occur in discrete fractures, most likely along by bedding planes.

METHODOLOGY

A new experimental site (Fig.2) has been established close to the riparian zone of the river Hafren, comprising 12 boreholes, drilled and sealed to different depths (1 m to 30 m), and 4 soil stations, in order to study temporal trends in sub-surface flow and chemistry. The aim of this study was to monitor physical (Haria and Shand 2003) and chemical changes in the stream and soils and groundwater of the riparian zone of the Hafren (Fig.1), both seasonally and more intensively during storm events.

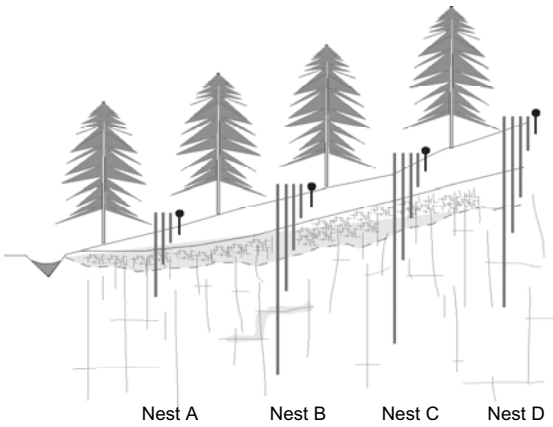

Figure 2. Schematic representation of the nested instrumentation

RESULTS AND DISCUSSION

There is a significant amount of spatial variation in the hydrochemistry of streams, soils and groundwater. Although the SEC varies little along the length of the Hafren stream, significant changes take place in the concentrations of most individual solutes (Fig.3).

The groundwaters show a strong hydrochemical zonation from acidic oxidising groundwaters in the shallower (< 10 m) fractured system to alkaline reducing groundwaters in fractures at 25 - 30 m depth (Fig.4). The deeper groundwaters are of Na-HCO_3 type and a strong smell of H_2S was observed during pumping.

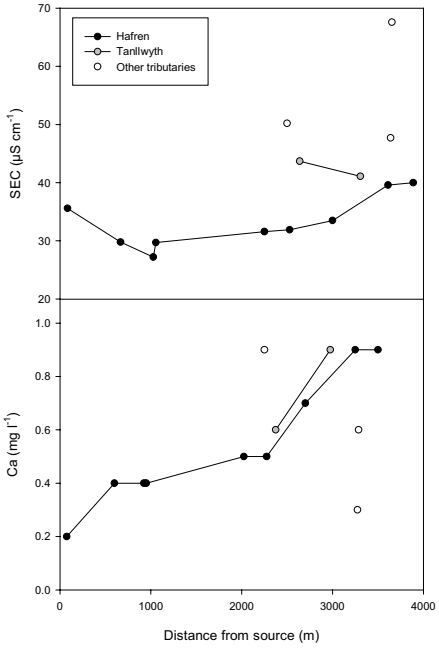

Figure 3. Variation in hydrochemical parameters along the Hafren stream

The shallow groundwaters display a change in stable isotopes (δ^2H and $\delta^{18}O$) towards more negative signatures in the winter months indicating recent winter recharge. This is not seen in the deeper groundwaters which remain relatively constant, implying different pathways and residence time.

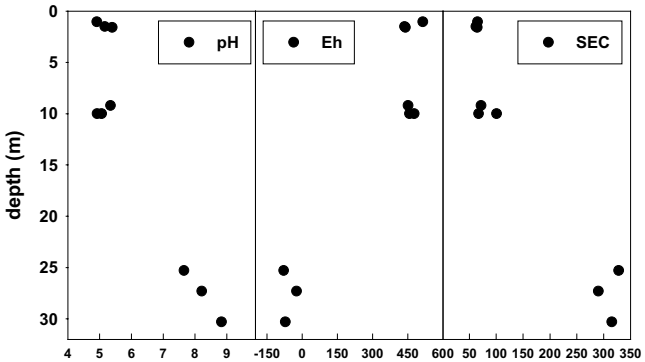

Figure 4. Depth variations in pH, Eh and SEC in the nested boreholes

Dating of the groundwaters was attempted using CFC's. The results indicated ages of 12-13 years for the shallow system and 43-46 years for the deep boreholes. The data for the shallow system is inconsistent with the seasonal stable isotope variations and show that a component (ca. 10-15 %) of older, deeper groundwater is discharging into the shallow fractures.

Intensive sampling of the Hafren stream, soils, groundwater and rainfall was completed during a storm event in January 2003 in order to determine temporal variations. Stream flow varied from 0.22 cumecs prior to the event up to 0.82 cumecs, with the peak stream hydrograph occurring a few hours after peak rainfall (Fig.5).

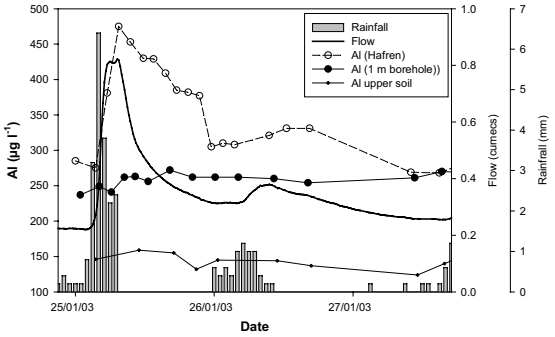

Figure 5. Temporal variations in rainfall, stream flow and Al concentration in the Hafren stream and shallow groundwater during a storm event

Stable isotope measurements (δ^2H) during the event showed that peak-flow in the stream is dominated by pre-event water with the direction of change being opposite to that in the rainfall and towards the shallow groundwater. Only during the tail of the recession was there a small increase towards rainfall.

The concentrations of Al in the stream responded rapidly, particularly during the rising limb of the stream hydrograph, whilst there was a much more subdued increase in the shallow groundwater (Fig.5). Significant discharge of water to the stream was seen along the river banks during the event, which contained similar Al concentrations (475 µg/l) to the stream during peak flow. Such discharge to the stream was considered to represent soil water. However, the deeper soil piezometers above the stream were generally dry and could not be sampled; and concentrations of Al in the shallow soils remained relatively low in the few cases where they contained free water (Fig.5). In addition, the chemistry of these discharge waters is almost identical to that of the shallow groundwaters, with the exception of Al and DOC. Therefore, it seems likely that these discharges represent upwelling groundwater which pick up soil-derived solutes as they move through B-C horizon soils in the riparian zone of the river. This scenario is consistent with radiogenic isotope data which could only be explained by the stream water representing a mixture of rainfall and groundwater (Shand *et al*. 1997) and also supported by hydrogeological data from the boreholes (Haria and Shand 2003) which indicate discharge of groundwater into the lower soil horizons and in the riparian zone.

The combination of chemical and physical data is helping to elucidate the transport mechanisms of rainfall through upland catchments and the data are pointing towards a dominant role for rapid transport through the upper bedrock. The high secondary permeability of such fractured rocks, in contrast to previously held views that these represent impermeable sealed catchments, helps to explain previous inconsistencies, both between physical and chemical data and between different natural isotopic and solute tracers.

REFERENCES

Haria A, Shand P (2003) Riparian groundwater processes in an upland fractured aquifer, mid-Wales: Implications for stream flow generation and water quality. This volume

Neal C, Robson AJ, Shand P, Edmunds WM, Dixon AJ, Buckley, DK, Hill S, Harrow M, Neal M, Wilkinson J, Reynolds B (1997) The occurrence of groundwater in the Lower Palaeozoic rocks of upland Central Wales. Hydrology and Earth System Sciences 1:3-18

Shand P, Darbyshire DPF, Gooddy DC, Edmunds WM, Neal C (1997) $^{87}Sr/^{86}Sr$ as an indicator of flowpaths and weathering *rates in the Plynlimon experimental catchment, Wales, UK Journal of Analytical Abstracts 2(2):*296

Groundwater residence time in crystalline rocks

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A b s t r a c t: A general meaning prevails that shallow and fast groundwater circulation prevails in complexes of fissured crystalline rocks while deeper and slow circulation is considered to predominate along tectonic zones of deep-reaching faults as indicated by high temperatures of thermomineral springs in tectonically affected crystalline regions. In some of the crystalline regions of the Bohemian Massif, isotope dating was used to clarify this problem in measuring the residence time of groundwater. Surprisingly, apart of modern groundwater in the shallowest weathered and fissured zone, even the groundwater residence time beyond the deep-reaching tectonic zones is often high. Values in the range of thousands of years have been established in relatively shallow, only 100 m deep borehole in fissured metamorphic rocks covered with less permeable eluvia.

INTRODUCTION

The Bohemian Massif is a part of the Variscan orogenic structure in the western part of the Czech Republic in central Europe. After several earlier orogenies, its tectonic development culminated during the Late Paleozoic. It consists of large extensive metamorphic units in different metamorphic stages and pierced by granitoid plutons.

In central and western Bohemia, the metamorphic units turn to non-metamorphosed strata of the Proterozoic and Lower Paleozoic. The folded pre-Variscan rocks are covered by later sedimentary sequences of the Upper Palaeozoic, Cretaceous and Tertiary.

In general, the whole system is affected by two conspicuous phases of tectonic activity: the Variscan metamorphism, folding and fracturing and the Tertiary fracturing and fissuration (accompanying the Alpino-Carpathian orogeny) of the whole consolidated block. The whole region has been uplifted since the Tertiary. The complex tectonic development has caused a variegated system of fissuration. Moreover, the permeability of the fissured zone is affected by the cover of weathering products at the surface. After the Variscan orogeny, the surface of the folded and fissured crystalline rocks was exposed to a long period of denudation, weathering and peneplenisation. This was interrupted by the Tertiary phase of fault tectonics, which gave origin to systematically arranged tectonic zones. It caused the uplift of large regional blocks, changed the morphology of the surface, changed the hydraulic gradients of streams and groundwater and caused deep erosion of streams below the level of the old surface. According to the petrological character of the bedrock, the weathering products are either arenaceous and permeable (as, e.g., the arenaceous eluvia of granitoid rocks) or clayey and less permeable (as, e.g. the clayey eluvia of cordierite gneisses in the Moldanubian region of Southern Bohemia). These phenomena seem to be the controlling factors of the groundwater circulation and they also affect the groundwater residence time as demonstrated by isotope groundwater dating.

METHODS USED

The presented paper is based on the results of groundwater dating in the crystalline regions of the Bohemian Massif. To establish the groundwater residence time, radiocarbon dating was used (Libby 1952) which was adapted by Münnich (1957) for dating of groundwater. Radiocarbon dating was combined with tritium and stable isotope analyses of light elements. This approach was found adequate in the hydrogeological conditions of the former Czechoslovakia (Šilar 1976). The regional investigation was focused partly to the Moldanubian region in southern Bohemia formed by crystalline schists pierced by granitoid plutons, partly to the tectonic zones accompanying the Tertiary faults in the petrographically variegated crystalline zones in northern Bohemia and Moravia with deep-reaching thermal water circulation. Neither the thermal springs containing magmatic carbon dioxide, which prevents the use of radiocarbon dating, nor the warm springs of the deep sedimentary basins of the sedimentary platform units, were included into the conclusions.

EVALUATION OF RESULTS

To compare the groundwater residence times in various geological structures, the groundwater radiocarbon ages were calculated uniformly considering its initial activity 85 percent of modern carbon (p.m.c.) as determined empirically (Vogel 1967, 1970;.Münnich and.Vogel 1959; Geyh 1972; Verhagen *et al.* 1991). In crystalline rocks and in rocks with a low amount of calcium carbonates in their weathering products, the initial ^{14}C activity of groundwater and the resulting ^{14}C ages can be assumed higher. Initial activities of 90 and 95 p.m.c. would result in ages higher by about 460 and 890 years, respectively. This empirical approach cannot be used if the radiocarbon balance is influenced by carbon dioxide of magmatic origin. Such cases were excluded from the evaluated data and need not to be considered in the areas compared in this paper. From the gained results, only those were evaluated which had not been influenced by factors, which could cause fundamental errors.

For confined aquifers, the piston flow model has been considered in which the radiocarbon age corresponds to the groundwater residence time. For unconfined aquifers, the radiocarbon age of groundwater can be considered equal to its mean weighted residence time for ^{14}C ages up to 5000 to 8000 years (e.g. Geyh 1971). Since higher radiocarbon groundwater ages do not occur in the unconfined aquifers, this assumption can be accepted without a considerable error.

To compare the results, the illustration by means of histograms was used (Šilar and Šilar 1995) which makes it possible to compare data of a larger area and suppress local influences in individual hydrogeological structures.

The results and histograms were divided into three sets:

1. Histogram of ^{14}C ages of groundwater from 17 springs within the Moldanubian region. It is obvious that, apart of three springs, almost all samples display a modern ^{14}C age thus indicating a shallow groundwater circulation.

2. Histograms of ^{14}C ages of groundwater from 5 boreholes of an intermediate depth between 25 m and 100 m deep and one borehole 731 m deep, all of them at the building site of the nuclear power plant at Temelín. All of them display a real, i.e. not modern, ^{14}C groundwater age. The samples do not contain tritium. Some of the boreholes have an artesian outflow from below a layer of clayey weathered and disintegrated cordierite gneiss.

3. Histogram of ^{14}C ages of groundwater of four thermal springs in four deep-reaching circulation systems at Jáchymov and Teplice (both in the Krušné hory tectonic zone) and at Janské Lázně and Velké Losiny (both in the Sudetic tectonic zone). All of the samples show Pleistocene origin of thermal water.

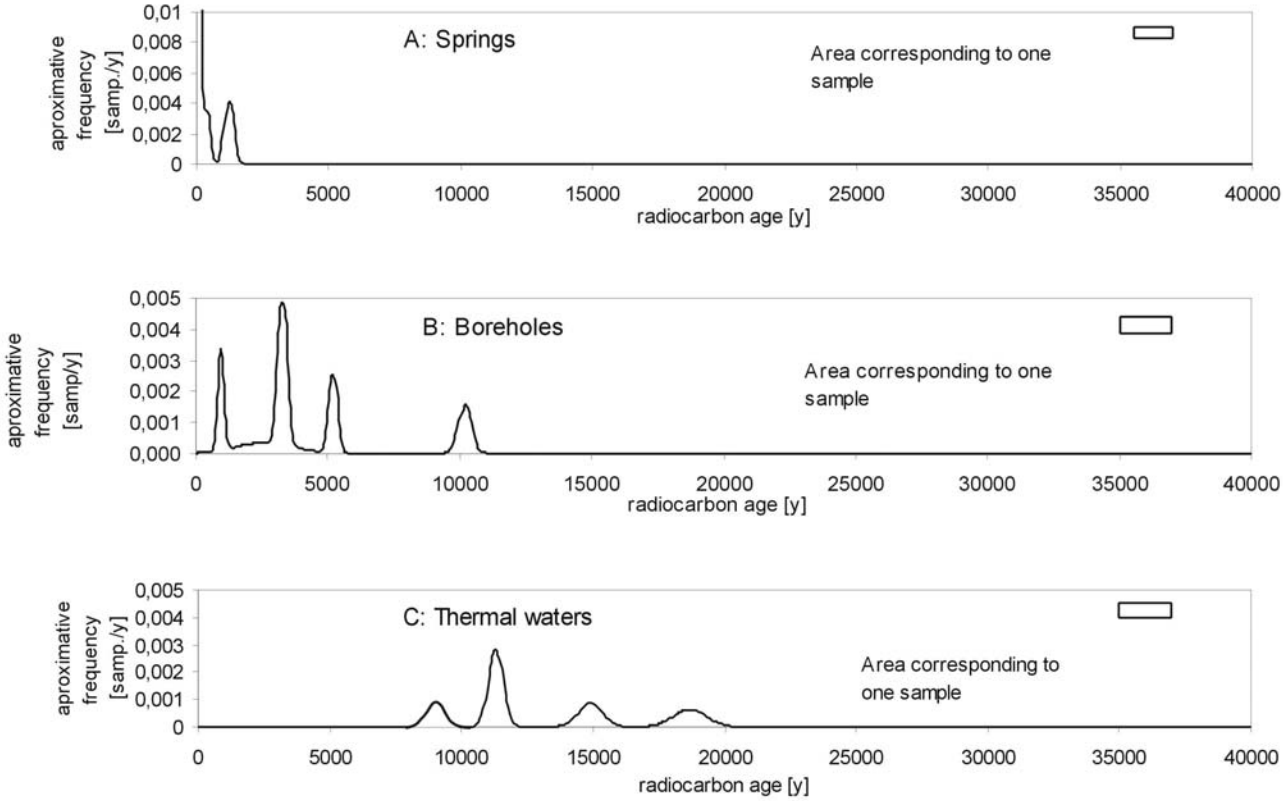

Figure 1. Histograms of radiocarbon ages

CONCLUSIONS

A new insight into the role of hydrogeological properties of the crystalline rock environment has been gained by compiling isotope data gathered within the Bohemian Massif by means of isotope groundwater dating. It indicates that slower and deeper groundwater circulation exists in the fissured zone below a shallower zone of less permeable weathered rocks. The fissures of the weathered zone at its bottom seem to be clogged with the clayey weathering products which separate the upper aquifer in eluvia from the lower fissured zone below. The water in the fissured rocks is sometimes confined, the upper aquifer in the weathered rock is sometimes perched, depending on the local morphology and piezometric conditions.

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Table 1 Samples

	Springs	Boreholes	Thermal waters
Number of samples	17	6	4
Number of recent samples	14	0	0
Average age	182	4591	12515
Average age (excl. recent)	-	3384	11330

REFERENCES

Geyh MA (1971) Die Anwendung der ^{14}C-Methode. Clausthaler tektonische Hefte, 11, Clausthal-Zellerfeld

Geyh MA (1972) Basic studies in hydrology and ^{14}C and ^{3}H measuremenets. Proc Int Geol Congr, 24th Sess., Sect.11, Hydrogeology: 227-234, Montrea.

Libby WF (1952) Radiocarbon dating. - 2nd ed.,5th imp. 1965, The University of Chicago Press, Chicago, London

Münnich KO (1957) Messungen des ^{14}C-Gehaltes von hartem Grundwasser. Naturwissenschaften, 44 (2), Springer-Verlag 32-33, Berlin, Göttingen, Heidelberg

Münnich KO, Vogel JC (1959) ^{14}C-Altersbestimmung von Süsswasser-Kalkablagerungen. Naturwissenschaften 46(5):168-169

Šilar J (1976) Radiocarbon groundwater dating in Czechoslovakia - first results. Věstník Ústředního ústavu geologického 51:209-220

Šilar J., Šilar J. (1995) Using environmental isotopes for groundwater flow analysis in basinal structures. Proceedings Application of Tracers in Arid Zone Hydrology, In. Adar EM, Leibundgut C (eds), IAHS Publication 232:141-150, Wallingford, U.K

Verhagen BT, Geyh MA, Fröhlich K, Wirth K (1991) Isotope hydrological methods for the quantitative evaluation of groundwater resources in arid and semi-arid areas. Research reports, Federal Ministry for Economic Cooperation:1-164, Bonn

Vogel JC (1967) Investigation of groundwarter flow with radiocarbon. In: Isotopes in Hydrology, IAEA,355-369, Vienna

Vogel JC (1970) Carbon 14 dating of groundwater. In: Isotope Hydrology, IAEA, 225-239, Vienna

Estimation of groundwater resources in hard-rock aquifers of India

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A b s t r a c t : In India, hard rocks occupy about 2/3 rd of the total surface area of the country. Steep increase in population which crossed one billion mark in the beginning of this century has put a greater stress on the availability of water. Therefore, a realistic assessment of ground water resources in these terrains is of importance for the socio-economic development of the country.

DISTRIBUTION OF THE HARD ROCK FORMATIONS OF INDIA

From the hydrogeological point of view, the hard rocks of India can be broadly classified into the following four types (Singhal and Gupta 1999).

1. Igneous and metamorphic rocks excluding volcanic and metasedimentary rocks in the Precambrian shield and mobile belts: these rocks cover an area of roughly 100,000 km^2, extending from Kanyakumari in the south to Delhi in the north over a distance of about 3000 km and encompassing the greater part of Peninsular India.
2. Volcanic rocks: These are mainly represented by the Deccan Traps of Cretaceous- Paleocene age occupying an area of about 500,000 km^2 in central and western parts of India. The Deccan Traps are of basaltic composition and consist of a number of flow units. Their maximum thickness is about 5 km along the western coast. The thickness decreases from the west towards east. The other suit of volcanic rocks is of Rajmahal traps of Jurassic age in parts of Bengal and Bihar in eastern India.
3. Hard sedimentary rocks viz. sandstones and shales (excluding carbonate rocks), covering an area of about 200,000 km^2 in Andhra Pradesh, Karnataka, Rajasthan, Madhya Pradesh, Uttar Pradesh, Bihar , Uttranchal, Chattisgarh and Jharkhand.
4. Carbonate rocks, mainly limestones, deposited in marine environments ranging in age from Pre-Cambrian to Tertiary.

METHODOLOGIES FOR THE ESTIMATION OF GROUND WATER RESOURCES

Introduction

The Government of India over the past 25 years constituted several committees to assess the ground water resources of the country. However, due to the paucity of required data and incomplete understanding of the various hydrogeological parameters, the estimates are only tentative and approximate. The Ground Water Estimation Committee of the Central Ground Water Board (CGWB) has reviewed the existing methodologies (CGWB 1997). Keeping in view the importance of hard rock formations, another committee was constituted in 2001 to look into the problems of ground water estimation in the hard rocks.

Groundwater balance equation

One of the approaches in the estimation of total recharge is to prepare the water balance of the saturated aquifer by balancing the input and output over a selected time interval.

The main problems in the estimation of recharge from water balance equation is due to the uncertainties in estimating reliably the inflow and outflow as well as proper delineation of the aquifer, estimation of specific yield and ground water draft from wells etc. It is generally assumed that any inflow into the basin from the adjoining area is equal to the outflow from the basin to the down gradient region.

The equation can be used for the year as a whole or for different seasons in the year separately. In India, it is preferred to prepare the ground water balance separately for the monsoon and non-monsoon periods from climatic and development point of views.

Geographic unit for ground water recharge estimation

The common practice in India has been to assess the ground water recharge for an administrative unit, namely a block, called locally as taluqa. Although such an approach is convenient from development point of view but it does not represent a natural hydrogeological unit. As an alternative, some states have adopted watershed as the unit for ground water assessment. In hard rock areas, water balance studies taking water shed as a unit may be more appropriate. A watershed may further be sub-divided into different hydrogeomorphic units. This would also facilitate the computation of weighted averages of water level fluctuation and specific yield data.

RECHARGE ESTIMATION

The estimation of recharge on a regional basis is usually difficult especially in hard rock formations due to their heterogeneity, complexity of flow system including throughflows in fractures.

The recharge takes place mainly by two processes, i.e. direct regional recharge by infiltration over wide areas and recharge along watercourses and from lakes etc. The direct recharge from rainfall is more significant in areas of high rainfall while in areas with low rainfall, the second mechanism is more effective. Studies in arid and semiarid terrains of Africa indicate that where rainfall is less than 400 mm, recharge from direct infiltration is small or negligible. Therefore, ground water development is mainly restricted from river alluvium or regolith in many parts of southern Africa.

The ratio of recharge to rainfall in hard rocks is usually between 9% to 13% depending on topography, hydrogeology and rainfall characteristics. In the crystalline rock terrains of Sahara in Western African Shield, which has semi-arid climate (rainfall about 500 mm per year), the recharge is 2 to 12 % of rainfall (Lloyd 1999). The average annual rainfall in India is about 1170 mm. However, its distribution is greatly uneven both in space and time, varying from about 200 mm in the north-western parts to more than 4000 mm in the north-eastern part of the country. The thickness of the unsaturated zone is also important as it limits the volume of water, which can be accepted by the aquifer.

Ground water level fluctuation method

This method is based on water level fluctuations between pre-monsoon and post-monsoon periods and the specific yield of the zone of the water level fluctuation. It is comparatively a simpler method. However, estimation of specific yield from pumping tests, especially in hard rock areas, is quite problematic.

Tritium injection method

This methodology provides spot measurements of recharge by monitoring the vertical movement of injected tritium.

This method has given recharge values varying from about 5 to 15% of rainfall in the hard rock terrains of India (Rangarajan and Athavale 2000)

Studies in the hard rock terrains covered with black cotton soil in basaltic terrain and red lateritic soil in granitic areas indicate that a minimal rainfall of about 246 mm and 412 mm are required for initiation of deep percolation in red and black cotton soils respectively. However, all of this infiltered water will not be available for utilization as part of it will be lost to base flow and effluent seepage to surface drainage system. This also does not include other sources of recharge such as return flow from irrigation. Rapid flow through fractures may also not provide realistic values of recharge obtained by tritium injection method.

Ground water base flow method

Ground water base flow contribution to stream flow is controlled mainly by annual precipitation, relative relief and hydrogeological conditions. In the basement rocks of Malawi and Zimbabwe, base flow contributions to stream flow, expressed as a fraction of rainfall, range from zero to 25% (Farquharson and Bullock 1992). Recharge estimated from base flow should be considered as a minimum because recharged water can be lost to evaporation through a number of components of the hydrological cycle before being measured at a gauging station. This method of estimation of recharge has been only limitedly used in India due to paucity of adequate gauging stations. However, this method holds greater promise for the estimation of recharge in hard rock terrains.

REFERENCES

CGWB (1997) Ground Water Resources Estimation Methodology, Report of the Ground Water Resources Estimation Committee, Ministry of Water Resources, Govt of India

Farquharson FAK, Bullock A (1992) The hydrogeology of basement complex region of Africa with particular reference to southern Africa. In: Wright EP, Burgess WG (eds) The Hydrogeology of Crystalline Basement Aquifers in Africa. Geol Soc London Special Publ 66:1-27

Lloyd JW (ed) (1999) Water resources of hard rock aquifers in arid and semi-arid zones. Studies and Reports in Hydrology 58, UNESCO

Rangarajan R, Athavale RN (2000) Annual replenishable ground water potential of India – an estimate based on injected tritium studies. J Hydro 234:38-53

Singhal BBS, Gupta RP (1999) Applied hydrogeology of fractured rocks, Kluwer Academic Publishers, Dordrecht, The Netherlands, 400 pp

Groundwater occurrence in fractured rocks - spatial zonality and temporal changes (Experiment results from Sudety Mts. - Poland)

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A b s t r a c t : Results of four-year field measurements on groundwater recharge and discharge in crystalline formation in the Śnieżnik massif (Sudetes - SW Poland) are presented. The experimental field station was equipped with a lysimeter (recording the infiltration rate), an electronic hydrograph (collecting data on groundwater flow from an abandoned mine adit) and refers to an observation well, and a gauging point aimed to record the total flow in the Kamienica River. Different methods showed variable groundwater recharge from 18 to 65 % of precipitation. Based on the tritium content in water and discharge variation the model of a flow system was constructed. Triple zones profile of the catchment under study are illustrated. Results indicate long residence time (7-10 years) of groundwater in deeper system of water flow.

PLACE

Direct and detailed measurements on groundwater recharge and discharge in relation to the possible controlling phenomena were conducted under natural conditions of the experimental Kamienica River catchment - in the Śnieżnik massif Western Sudetes (SW Poland). The area is underlain by crystalline rocks of the Lądek-Śnieżnik metamorphic formation, being one of the main components of the Orlica-Śnieżnik dome (Don *et al.* 1990).

Two main lithologically different rock groups have been distinguished here: that of schist and gneiss associated with quartzite and that of crystalline limestone, erlan and amphibolite. In general, these are ca 500 Ma orthogneisses emplaced into their Neoproterozoic staurolite-grade envelope, metamorphosed and intensely deformed under amphibolite facies conditions during Carboniferous times (e.g. Turniak *et al.* 2000)

The annual atmospheric precipitation in the catchment area is high and ranges from 1150 to 1676 mm for the period of 1997-2001year. The study area is located in a mountainous climatic province with an average air temperature of 6.69 ^{o}C. This area represents one of those best documented in the Sudetes (see the monographic study edited by Jahn, Kozłowski nad Pulina 1997).

METHODS

The infiltration rate has been evaluated based on lysimeter data together with analysis of daily values of precipitation and air temperature. The drainage process study was based on daily values of groundwater runoff recorded at the outlet an abounded mine adit. In order to evaluate the discharge rate and the yield of zones drained by the adit, the hydrograph separation method was applied. The recharge value was also determined from water level fluctuation data coming from a supplying well (WOP) and an observation well SO_4. The groundwater chemical composition study include tritium, ^{18}O, radon and radium concentration.

RESULTS

The lysimeter data concerning the period of 1997-1999 showed that the infiltration rate equalled 18-22 % of the precipitation value and that the maximum amounts of percolating water occurred in two periods. The first one took place in March and April, whereas the second one was recorded in July to August. Precise electronic records of infiltration changes in years 1999-2000, which showed that three intense groundwater recharge events occurred mainly at the turn of July and August 2000, in March 2001 year and from December to January 2002 year.

A preliminary study indicates that the initial precipitation over the investigated area ranges between 20 to almost 50 mm.

The records of groundwater runoff for the Kamienica River obtained using hydrograph separation method are presented. The recorded values obtained are almost twice as high as those yielded by lysimeter gauge. The water level fluctuation measured in a 14 m-deep well showed annual level changes of 1.6 to 2.2 m. The average groundwater level were recorded at 11.8 – 12.3 m below the ground surface. The results showed two maximum water level stages during the summer and spring. The observation well, located in the river valley near to the mine adit, showed low amplitude (0.93 m) of water level fluctuation. The estimated correlation between the precipitation and water level fluctuation in well SO_4 revealed two to three days' delay in water level rise with respect to the rainfall. Water level changes showed direct relationship to the discharge values of the Kamienica River.

The groundwater runoff from the area drained by the mine adit was recorded in 1997-2002. The drained area is a mountainous terrain located at 860 to 1426 m above the sea level; it covers ca 0.8 km^2. The discharge fluctuation showed a more or less regular pattern of annual and seasonal variation rhythm. Two main maximum stages are clearly visible in that pattern and they are accompanied by minor increase events, followed by long discharge recession periods. The increases of flow are sharp and rapid, which is considered typical of fractured aquifers. The annual water discharge from the adit of average is equal 22.1L/s, and 65.4 to 10.1L/s maximum and minimum respectively. The capacity values of the drained system (aquifer) and the discharge rates were evaluated from recession curve analysis using Mailett, Forksiewicz, Cotange and Burger formulae. The recession coefficient values can be classed into two or three groups. The first one is most frequently observed and ranges between 0.01 and 0.05, which is typical of shallow, local groundwater drainage. Lower values of the order of 0.001 to 0.005 are typical of deeper intermediate flow system (Staśko and Tarka 2001).

The measurements made in the river (during 1998 -2002) allowed a separation to be made of the groundwater runoff from the total discharge. The Kamienica River catchment drained highly elevated areas located at the altitude of 1426 down to700 m above the sea level and the gauging point covers an area of 7.34 km^2. The average total flow for the controlled area equals 0.499 m^3/s for the minimum discharge of 0.08 m^3/s, and the its highest value of 9.01 m^3/s. The evaluated average groundwater runoff equals 800 mm which is equivalent to 48-65 % of the recorded precipitation.

The groundwater composition in the study area showed low total dissolved solids value in the range of 30-90 mg/dcm^3 which is typical of ultra fresh water. The value of pH for the water from the adit was equal to 6.4 and showed increase in comparison with the earlier years.

The research on the radon and radium concentration in water (Przylibski *et al.* 2002) showed direct correlation of between the

fracture zone occurrence and the increase of these elements. The concentration of isotopes ^{222} Ra in water from the adit and well SO_4 are among the highest in Poland (1430- 1119 Bq/dm^3), whereas in the river water they are as low as up to single Bq/dm^3. The measured concentrations of radium isotopes – ^{226}Ra and ^{228}Ra also showed variable values varying between 0.011 to 0.006 Bq/dm^3. Tritium content in groundwater was measured as 24.6-10.6 ±0.6 TU during 1992-2002 years.

Based on the flow measurements and the hydraulic properties (from laboratory tests), a model of groundwater flow in a fractured medium was presented. In contrast to the piston flow model, three zones of different hydraulic properties have been assumed in the model here presented. The latter model was verified by calculation for three different hydraulic parameters scenarios.

The scheme is a result of measurements, calculation and interpretation of isotopic research of the tritium content in water samples. The tritium content in groundwater showed that the average water flow ranged from 150 m/year to 10 m/year in deep system circulation. The groundwater residence time in the catchment was evaluated as 7 to 10 years. The obtained results correspond to the data by Hoeg *et al.* (1999), and Aeschbach-Hertig *et al.* (1998). Similarly long water age and flow have been indicated by Ciężkowski (1990) and Zuber and Motyka (1994).

REFERENCES

Aaeschbach -Hertig W, Schlosser P, Stute M, Simpson HJ, Ludin A, Clark JF (1998) A ^{3}H/^{3}He study of groundwater flow in a fractured bedrock aquifer. Groundwater 36:661-671

Ciężkowski W (1990) A study of hydrogeochemistry of mineral and thermal waters in the Polish Sudetes Mountains (SW Poland) (in Polish) Scinetific Paper of Geotechnic's Inst Technical Univ. Monographic Series No 60/19, Wroclaw, 133 pp

Don J, Dumicz M, Wojciechowska I, Żelaźniewicz A (1990) Lithology and tectonic of the Orlica- Śnieżnik Dome, Sudetes-recent state of knowledge. N Jb Geol Palaont Abh 179, 2/3:159-188

Hoeg S, Uhlenbrook S, Leibundgut CH (2000) Hydrograph separation in a mountainous catchment combining hydrochemical and isotopic tracers. Hydrologic Processes, 14:1199-1216

Jahn A, Kozłowski S, Pulina M (1997) The massif of Śnieżnik-changes in the natural environment. (in Polish), Polish Ecological Agency, Warsaw, 320 pp

Przylibski TA, Staśko S, Szczepanowski S, Modelska M, Dorda J, Kozłowska B (2002) Preliminary results of determinations of radon and radium concentration in surface and groundwater in the upper part of the Kamienica River catchment (Snieznik Massif, Sudetes, SW Poland).(in Polish) Prz.Geol 50(5):436-440

Staśko S, Tarka R (2001) Groundwater flow in fractured hard rocks based on field data from Sudety Mts., SW Poland. In: New approaches characterising groundwater flow 2:1069-1072, A A Balkema Pub, Munich

Turniak K., Mazur S. and Wysoczański R. (2000): SHRIMP zircon geochronology and geochemistry of the Orlica-Śnieżnik gneisses (Variscan belt of Central Europe) and their tectonic implications. Geodinamica Acta 13: 293-312.

Zuber A, Motyka J (1994) Matrix porosity as the most important parameters of fissured rocks for solute transport at large scale. J of Hydrology 158:19-46

Using recession curves to assess recharge in crystalline massif

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A b s t r a c t : There is large variability in type of spring recession in crystalline massifs. Calculations of recession coefficient based only on a single observation period could be misleading. Mangin's model appears more reliable than other recession models. It was shown by stream and spring discharge recession analysis. Stream discharge is sensitive to precipitation and springs should be preferred in reservoir volume estimation.

INTRODUCTION

Variation of spring and river discharge during low or no rainfall time period could be presented by recession curves. The groundwater recharge and hydraulic parameters of an aquifer can be estimated from recession models. For a homogenous medium a recession coefficient has a constant value for different drainage periods. However, for hard rocks this assumption is not valid. Due to heterogeneity the recession coefficient is not only a function of a water stage in the aquifer, but depends also on aquifer size, and effective porosity and permeability distributions. A small experimental watershed, located in Sudetes Mts. (SW Poland), was chosen to conduct field studies. Sudetes Mts. forms the north-eastern margin of the Bohemian Massif. Study area consists primarily of gneiss's, schist's, and locally of erlan rocks. A watershed is located at altitudes from 750 to 1100 m a.s.l.

SPRING'S RECESSION CURVES

Spring's discharge measurements were used to analyse a drainage process of crystalline massif aquifer. Three different time periods of low or no rainfall were chosen:
I 18.07-16.10.1992
II 01.05-10.07-1993
III 23.04-30.07.1994

During these time periods no infiltration into lysimeters located at depth of 0,9 m was observed. Discharges of six natural springs and one artificial outflow (an old mine shaft) were measured. Tab.1 shows physical characteristics of measurement points. Field recession curves were compared to theoretical models (Maillet, Tisson, Cotagne, Forkasiewicz and Paloc) and the best fitting model was chosen for each point and for each observation period (Stasko and Tarka 1994). Using determined recession model the values of recession coefficient for all observed outflows were calculated (tab.2). Large variability in recession type and different values of recession coefficient for a single spring is observed. There is no prevailing recession model valid for study area. Using determined models, the calculations of volumes of spring's reservoirs were made, however, there is a large uncertainty about correctness of calculated values. When field discharges are plotted in a logarithmic scale, the recession curves generally can be approximated by straight lines. There is a distinct split of recession lines into two or more parts with different slope (fig.1).

Observed recession type is consistent with Kowalski's theory (1992) for groundwater flow within clay regoliths of crystalline rocks. At the beginning spring is fed by saturated medium (filtration) and later it drainage's unsaturated medium (this is represented by different slopes of the recession line). Clay regoliths of the Sudetes Mts. can contain water in amount from several to 100 % of the void space. Laboratory experiments shown that constant saturated flow occurs for 70 % or higher saturation factor (Kowalski 1987). However clay regoliths usually contains less water then 70 % of the void space, and springs drainage unsaturated medium. For these conditions recession curves are of no use to estimate the total storage capacity of aquifers. For springs being fed by crystalline baserock the two-type recession is explained that at the beginning the outflow is from regolith surface cover and later only from fractured baserock. According to Scholler (1965) outflow from baserock could be described by Maillet's model. However field observations of this study point to Mangin's model as more accurate.

Table 1. Basic characterisation of springs

Spring	Lithology	Altitude [m a.s.l.]	Q_{max} [L/s]	Q_{min} [L/s]
K 1	gneiss	980	1,412	0,245
K 2	gneiss	980	1,395	0,347
K 15	erlan rocks	750	3,845	0,320
K 23	gneiss	880	7,925	0,434
K 25	gneiss	800	1,635	0,272
L 1	gneiss	895	3,381	0,598
L 2	gneiss	1000	10,4	0,260
L 5	schist	1010	4,864	0,015
L 6	schist	870	1,632	0,106
S 1	gneiss	860	42,7	16,5

Table 2. Characterisation of springs regression

	Period					
	I		II		III	
Spring	Equation	Coefficient	Equation	Coefficient	Equation	Coefficient
K 1	Maillet	0.00977	Forkasiewicz	0.0576	Forkasiewicz	0.02121
K 2	Tisson	0.00357	Forkasiewicz	0.0495	Forkasiewicz	0.02109
K 15	Maillet	0.01347	Maillet	0.01357	Maillet	0.01448
K 23	Cotange	0.00844	Cotange	0.0892	Forkasiewicz	0.02684
K 25	Forkasiewicz	0.06920	Forkasiewicz	0.0558	Forkasiewicz	0.03718
L 1	Maillet	0.00532	Maillet	0.01224	Cotange	0.01613
L 2	Tisson	0.00923	Cotange	0.2380	Cotange	0.08979
L 5	*		Tisson	0.07100	Tisson	0.06096
L 6	Maillet	0.04853	Forkasiewicz	0.0707	Forkasiewicz	0.05402
S 1	*		Forkasiewicz	0.00002	Cotange	0.01185

* - undefined

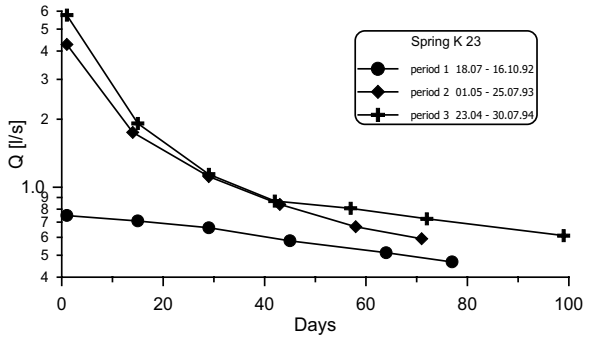

Figure 1. Changes of tempo regression in dependencies from time period

Most of permanent springs in Snieznik Massif have relatively constant water temperature (a maximum amplitude is 2°C). Constant water temperature and small fluctuations of spring discharges allows one to postulate that spring's outflow originates in fractured baserock. Based on this assumption Mangin's model was used to analyse recession process. Tab.3 presents results of the total storage volume of springs' reservoirs calculations by fitting method (that is, chosen the best model, see tab.2) and by Mangin's model. The sum of local and regional reservoirs volumes (V_l and V_r, respectively) is two, three times higher then value determined by fitting method. Naturally, a question which method is more adequate arises. Capacity indicator calculations could be an answer:

$$\Delta V = \frac{V}{A}$$

where: V - storage volume of spring's reservoir; A - reservoir area.

Table 3. Volume of water of reservoirs drained by each outflow

Spring	Period	Fitting method	Mangin's method	
		V_t [m^3]	V_l [m^3]	V_r [m^3]
K 23	II	4167	2495	10448
K 25	II	-	60	11196
L 2	II	3630	5548	9866
L 5	II	5531	2822	2184
L 6	II	-	557	9067
L 1	III	18110	3003	41498
S 1	III	304040	19024	545325

Table 4. Capacity indicator of reservoirs drained by each outflow

Spring	Area [m^2]	Fitting method	Mangin's method	
		ΔV_t [m]	ΔV_r [m]	ΔV_l [m]
K 23	133270	0.031	0.078	0.019
K 25	49003	-	0.228	0.001
L 1	76666	0.236	0.541	0.039
L 2	166817	0.022	0.059	0.033
L 5	60071	0.092	0.036	0.047
L 6	46496	-	0.195	0.012
S 1	1282969	0.237	0.425	0.015

Values of reservoir area A for particular springs were estimated by multiplying the total volume of discharge from the spring in the whole observation period (1992-1994) and average infiltration from the same time period (Tarka 1997). Results of capacity indicator calculations are presented in tab.4. Mean wage capacity indicator for natural springs (K 23, L 1, L 2 and L 5) is -0.072 m, and for all outflows (adding an old mine shaft S1) is -0,195 m according to fitting method. For Mangin's model these values are 0,145 m and 0,354 m (using regional reservoir volume). Use of an average specific yield as 1 % allows calculating saturated thickness of baserock aquifer. Mangin's model gives the value of saturated thickness of 35 m, when according to fitting method the saturated thickness is only 20 m. Boreholes in study area indicate 40 m of weathering fractures zone. Thus Mangin's model seems to be more applicable for crystalline rock aquifers.

Based on recession analysis results a residence groundwater time was calculated. Average annual groundwater recharge for study area is 0,55 m (Tarka 1997). The renewing time for groundwater are from 3 (according to fitting method) to less then 1,5 times a year (Mangin's model). These are very large rates of flow. Isotopic composition of groundwater in the study area is not consistent with these renewing rates. There is no variability in isotopic composition during the year (Ciezkowski *et al.* 1990). The conclusion is that real reservoir's volumes are higher then ones estimated by Mangin's model. However Mangin's model still gives more reliable results then fitting method.

With the correction that some amount of aquifer is drainage by streams, the capacity indicator calculations on the basis only of spring discharge recession should be lower then recharge. Incorporating this additional stream drainage is a logical postulate.

SUMMARY

There is large variability in type of spring recession in crystalline massifs. Calculations of recession coefficient based only on a single observation period could be misleading. Mangin's model seems to be more reliable than other recession models. This was shown by stream and spring discharge recession analysis. Stream discharge is sensitive to precipitation and springs should be preferred in reservoir volume estimation.

The discrepancies were observed for recession coefficient for the same spring in different time periods and in single observation period for springs in the same area. As mentioned before, recession coefficient is not only a function of stage of water in the aquifer, but depends also on aquifer size and porosity, and permeability distributions. Heterogeneity of crystalline rock aquifers is the direction in which future study has to be concerned.

REFERENCES

Ciezkowski W (1990) Studium hydrogeochemii wód leczniczych Sudetów polskich. Prace Nauk Inst. Geotechniki Polit. Wrocl. nr 60, Monografie 19, Wroclaw 128 pp

Kowalski S (1987) Drenaz wody w warunkach laboratoryjnych na przykladzie wybranych utworów kenozoicznych Sudetów i ich przedpola. Geologia Sudetica v XXII Ossolineum, Wroclaw

Kowalski S (1992) Czynniki naturalne warunkujuce wystêpowanie wód podziemnych w regionie sudeckim. Acta Univ Wratisl, Prace Geolog-Mineral XXV, Wroclaw 68 pp

Schoeller H (1965) Hydrodynamique dans le Karst. Hydrologie des roches fissurees, vol. 1. AIHS, Bruksela

Stasko S, Tarka R (1994) Obliczanie zasobów wód podziemnych w obszarach górskich na przykladzie badañ wybranych zlewni Sudetów. Mat. Konferencyjne I Sympozjum „Bilansowanie zasobów wodnych w dorzeczu Odry". Zeszyty Nauk. Akademii Rolniczej we Wroclawiu nr 248, Konferencje V, Wroclaw 279-285

Tarka R (1997) Zasilanie wód podziemnych w górskich masywach krystalicznych na przykładzie masywu Śnieżnika w Sudetach., Acta Univ Wratisl Prace Geol-Mineral nr LVI, Wrocław 66 pp

Conceptual model of a regional karstic hydro-structure based mainly on a long-term isotopic survey

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A b s t r a c t : South Dobrogea (Romania) represents, due to its natural and anthropic features, a very interesting area especially for hydrogeologists. There are two superposed calcareous aquifers - the upper aquifer (Sarmatian) and lower aquifer (Barremian - Jurassic) - in the region that constitute a karstic system of a strategic importance. The isotopic monitoring (^{3}H, ^{14}C, ^{13}C, D, ^{18}O) was performed over the last 25 years by an integrated research of all natural types of waters, in order to improve the knowledge of hydrogeological parameters and of the regional pattern flow. The main isotopic characteristics of meteoric and surface waters are also briefly described in the paper. Within the karstic system, our study focused on the lower aquifer for which an up-to-date regional conceptual model was carried out by correlating all hydrodynamic and isotopic information.

INTRODUCTION

The South Dobrogea represents a region where there is a karstic system of strategic importance for Romania. Until 1973 the classical hydrogeological prospecting has not been able to give a definitive picture of the groundwater patterns. Beginning with 1982 a sampling network – including not only groundwater but all the waters types of hydrological cycle – was maintained unchanged and all environmental isotope (tritium-^{3}H, radiocarbon-^{14}C, carbon 13-^{13}C, oxygen 18-^{18}O and deuterium D) have been analysed. Additionally, during 1994 year $\delta^{18}O$ and $\delta^{15}N$ in NO_3^- measurements have also been carried out. This isotopic database covers about a quarter of century and includes now more than 2000 analyses.

REGIONAL FRAMEWORK

South Dobrogea is located in the southeastern part of Romania, on the Black Sea shore, at about 44^0 northern latitude and 28^0 eastern longitude.

The karstic system of South Dobrogea is formed by two superposed aquifers, separated by an intermediate partially acviclude:

- Upper aquifer, in a calcareous Sarmatian (late Miocene) plate developed with more than 10 m thickness especially in the southeastern part of the region and

- Lower aquifer – economically very important - underlying most South Dobrogea, in a unitary and karstified limestone and dolomitic complex deposits of Jurassic and Barremian (Early Cretaceous) age. The thickness of the lower aquifer complex is about 1000 m in the southwestern part of South Dobrogea but decreases to about 400 m in the east and especially northeast (Siutghiol Lake area). This complex is descending from south towards north and northeast and it is affected by two main fault systems with NNE-SSW and respectively WNW-ESE directions. The last fault system, including the great overthrust Capidava-Ovidiu that represent the northeastern geological boundary of South Dobrogea, is younger and has a major hydrogeological significance.

DISCUSSION OF ISOTOPIC RESULTS

Meteoric and surface waters

Meteoric water was sampled in the Constantza meteorological station during 1980-1989 period. Tritium was measured in this entire interval. Concerning the surface waters, there are different natural water bodies (Danube River, Black Sea, salt and fresh water lakes) as well as a regional network of irrigation or transport channels. As these waters should constitute partially the recharge, they were systematic sampled, with the same yearly cadence as the groundwater. Tab.1 and Fig.1 show some results from 1986 year. It can be noticed that the stable isotope concentrations cover, at regional scale and at the same moment, a great range of values ($\delta^{18}O$ = -2.8 to -10.9 ‰ and δD = -20.0 to -68.8 ‰), consequence of diverse water types. Instead, for the same body water, during 1974-1996 period only small changes were registered, the most important being the progressive enrichment of Siutghiol Lake that we interpret as consequence of draught installed in the last 30 years. The relationship for all surface waters ($\delta D = 6.5*\delta^{18}O - 4.5$; $R^2 = 0.92$) is little different from MWL but our experimental points are grouped in two areas: one for the waters from Danube River and all the channels and another, with more negative values, for the waters from littoral lakes and the Black Sea.

Table 1. Comparative average isotopic composition of the main water types in South Dobrogea, May 1986

Water type	N*	^{3}H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	^{13}C ‰)
Meteoric water	1	31	-59.1	-9.0	-	-
Danube River	3	38	-64 .8	-10.1	-	-
Black Sea	2	28	-23.0	-3.6	-	-
Upper aquifer	12	15	-66.1	-10.0	43.2	-10.6
Lower aquifer	27	<5	-78.0	-11.1	18.4	-7.8

N* is the number of sampled points

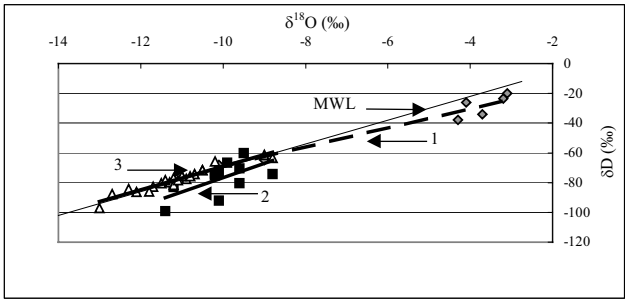

Figure 1. δD-$\delta^{18}O$ diagram for the surface waters and groundwater in the 1986

Key: 1.Surface waters: $\delta D = 6.5*\delta^{18}O - 4.5$, R = 0.96; 2. Upper aquifer: $\delta D = 9.6*\delta^{18}O + 18.9$, R = 0.40; 3. Lower aquifer: $\delta D = 7.9*\delta^{18}O + 9.9$, R = 0.93; MWL: Meteoric Water Line.

Karstic system waters

The karstic system and especially the lower aquifer were the target of our isotopic research in the last 25 years. From the entire period we chose three moments -1974, 1986 and 1996- as representatives from hydrogeological point of view and better illustrated by isotopic analyses.

Upper aquifer

The sampling of upper aquifer began in 1985 year in a permanent network constituted of 12 water points (boreholes, wells, and springs).

The areal distributions of oxygene-18 and radiocarbon are in agreement with the regional piezometric pattern showing gradients towards Black Sea. In Fig.1 is showed the correlation $\delta D - \delta^{18}O$ for the upper aquifer in 1986 year and its equation: $\delta D = 9.6*\delta^{18}O + 18.9$; $R^2 = 0.4$. It can been noticed that the contents of stable isotopes for these waters, with a dispersion great enough, are placed between those of the Danube and of the lower aquifer. This dispersion is probably the consequence of two factors acting especially along Black Sea littoral: the partially evaporated surface waters and the deeper ascending groundwater.

Lower aquifer

The study by environmental isotopes of this aquifer began in 1974 year in few points. After 1982 year 27 wells were selected as a permanent network for geochemical and isotopic sampling.

Tab.2 summarizes the isotopic results obtained in the three characteristic moments – mentioned above – and for the three boundary areas of aquifer.

The areal distributions of stable isotopes values were found almost unchanged in the entire research period. This stability is proved moreover by the high ($R^2 > 0.82$) correlation coefficient of $\delta^{18}O$ values measured during four years interval, in the same lab and locations. The low concentrations measured in 1974 emphasize a permanent contribution of deeper groundwater and therefore the great importance of tectonic in the upwards leakage especially in the Mangalia-Techirghiol Lake area.

Table 2. Time evolution of isotopic results for three characteristic areas of lower aquifer

Year	Recharge area (SE Ostrov)					Main discharge area (Siutghiol Lake)					Discharge area (Mangalia Lake)				
	^3H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)	^3H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)	^3H (TU)	δD (‰)	$\delta^{18}O$ (‰)	^{14}C (pMC)	$\delta^{13}C$ (‰)
1974		-64.6	-11.0	82.9	-9.2		-78.8	-12.5	10.4	-7.7		-78.2	-12.8	4.1	-7.3
1986	11	-63.3	-10.8	79.0	-9.4	<5	-77.0	-11.2	9.9	-8.0	<5	-86.4	-12.1	2.9	-7.3
1996	6	-72.0	-10.7			<1	-86.7	-12.2	10.9	-8.2	<1	-94.4	-13.1	0.9	-0.3

Concerning the tritium, it may be noticed that significant concentrations were measured only for some wells situated next to the Bulgarian border, in the southwestern part of the South Dobrogea – in Tab.2 named "recharge area (SE Ostrov)" - and in the East Medgidia bifurcation zone of the Danube-Black Sea Channel. Besides the information about the placement of the main intake area, these tritium values prove a almost good isolation over entire area against external influences except the area East Medgidia where there is an minor descending recharge (fig.2).

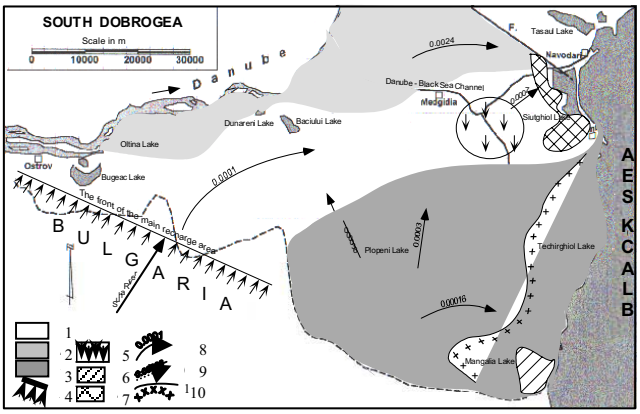

Figure 2. Hydrogeological conceptual model of lower aquifer, up-to-dated for 1996

Key. *Aquifer type:* 1. Shallow groundwater (^{14}C=20÷50 pMC, ^3H=0,8÷ 14,3 TU); 2. Partial confined aquifer (local covered by the Lower Cretaceous aquitard: ^{14}C=5,0÷10 pMC, ^3H=<0,8÷1,1 TU); 3. Confined aquifer covered by the intermediate complex aquitard: ^{14}C=1,0÷10 pMC, ^3H = < 0,8 TU); *Recharge:* 4. The front of the main recharge area ; 5. Adventive recharge (by surface water) area; Drainage: 6. Natural drainage area (Np below + 17 m); 7. Major (natural and anthropic conditioned) discharge area (Np below + 2m); *Groundwater hydraulic:* 8. Flow direction of groundwater, confirmed by isotopic means and the value of hydraulic gradient; 9. Flow direction of groundwater, suggested by underground hydraulic information but non-confirmed by radiocarbon; 10. Zero line of the area having the piezometric head above (until 15 m) than the upper aquifer.

The ranges of stables isotopes D and ^{18}O are, much or less, the same as other freshwaters in the region but the average values are more negatives. The equation of their correlation, $\delta D = 7.9*\delta^{18}O + 9.9$; $R^2 = 0.93$, is practically the same as MWL.

The progressive increase of this contribution after 1974, emphasized by a diminution of contents, seems to mean that in the last 25 years was a continuous overdraft which unbalanced the natural equilibrium of the two recharge component.

As the radiocarbon (Tab.2), the variation of measured ^{14}C activities for the same point is generally small except some areas (ex. Mangalia Lake) where the recharge conditions are changed during the last 25 years. Therefore, all isoline maps drawing up for the 1974, 1986 and 1996 moments show the same main features: a central SW-NE strip with higher concentrations, limited by two areals in which the water shows a progressive aging towards Mangalia Lake and Cernavoda town. The actual velocities obtained - 500 to 1,800 m/year in the central strip and only under 100 m/year in the Mangalia Lake area – differ up to two orders of magnitude from the values obtained previously. Despite the fact that few hydraulic flowing directions were found "no radiocarbon flow direction", these values are in agreement with velocities calculated hydraulically and suggest they are close to the "true values".

The main isotopic features can be synthesized (fig.2) by:

- Recharge area: mainly in the Pre-Balkan Platform (Bulgaria);
- Recharge water: precipitation, runoff, small rivers and probably from Danube River;
- Groundwater flow: the main direction is east-northeast, towards the Siutghiol Lake and the secondary is southeastward, towards the Mangalia Lake;
- Other inputs: upward leakage in the Techirghiol Lake – Mangalia Lake area and a minor descending recharge at East Medgidia area;
- Flow velocities: 500-1,800 m/year on the main groundwater flow and up to 100 m/year on the secondary one.

CONCLUSIONS

The isotopic long term survey of the waters from South Dobrogea allowed a comprehensive and integrative insight into the karstic system as theirs hydrodynamic parameters, boundary input and output conditions, assessment of vulnerability, etc. and the achievement for lower aquifer of an improved conceptual model.

TOPIC 3

CHEMICAL, PHYSICAL AND ISOTOPE PROPERTIES OF GROUNDWATER IN FRACTURED ROCKS

- Properties of shallow and deep groundwater
- Saline waters, brines, salinization process
- Thermal and mineral waters
- Regional and local hydrochemical studies

Hydrochemical and environmental isotope properties of shallow groundwater of the Basement rock aquifer in Offa Area, SW Nigeria

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A b s t r a c t : The study area covers about 42.25 Km^2 and is defined by longitudes 4° 42.8′ and 4° 46.2′ E and latitudes 8° 9′ and 8° 12.5′N. The aquifer system in the study area is formed by weathered and fractured basement. The Basement rocks of the district comprise of gneisses, migmatites and granites. Offa town is underlain by the hard-rock suite consisting mainly of biotite gneiss with lenses and bands of biotite schists and pegmatite intrusions. Available borehole lithological logs in the area revealed that weathering is not deep and that the rocks have been jointed and fractured severely. These joints and fractures have, to a large extent, controlled the flow direction of the rivers in the area. Results of field analysis of the water samples have shown a pH range of 6.1 - 7.9; electrical conductivity of 34 -1, 013 µS/cm and total dissolved solids (TDS) of between 32 to 851 mg/L with a median of 819 mg/L suggesting the occurrence of low mineralized waters. The predominant anions concentrations are in the order $HCO_3 > Cl > SO_4$ and $HCO_3 > SO_4 > Cl$ for groundwater and surface water respectively while that of cation concentrations are Ca > Na > Mg and Na > Ca > Mg. The main water type in the area is essentially $CaHCO_3$ with the exception of three samples that shows Na-Cl water type. However, in all the cases, the average concentration of $Ca^{2+} + Mg^{2+}$ exceed that of $Na^+ + K^+$. This is a reflection of the predominant rock type in the investigated area where pegmatites (highly prone to weathering) are common intrusions in the gneissic rocks of the area. The $\delta\,^2H$ versus $\delta\,^{18}O$ diagram indicates that the water types in Offa area were derived from local meteoric waters as majority of the groundwater samples plots around the Meteoric Water Line and have deuterium excess less than 10. This indicates similar recharge conditions and an isotopic enrichment by evaporation.

INTRODUCTION

Offa township lies approximately 45 km SE of Ilorin, the Kwara State capital city. Its closeness to the state capital couple with the good network of roads and railway is responsible for the growing commerce and population in this area. Over the years, commercial activities in this area have steadily grown attracting more people to the urban centres and consequently increasing groundwater use. Public water supply from a dam across Oyun river, with storage capacity of 20 million gallons and daily supply of 700,000 gallons of treated water, has failed to meet the growing demand for water in the area as a result of population increase and industrialisation. Therefore in order to meet the increasing water needs for domestic and industrial purposes there has been heavy dependence on groundwater.

A research project to assess the water resources and quality of groundwater in this area has been initiated. In the preliminary investigations more than 100 wells (mostly hand-dug wells and some boreholes) have been studied under the student research project scheme (Johnson 2000, Oyetakin 2000, Shonibare 2000) and sampled for physical and chemical analyses. The overall aim is to get adequate information on groundwater isotopic and chemical characteristics with possible origin dynamics and recharge.

GEOLOGY AND HYDROGEOLOGY

Geologically, Offa and its neighbouring towns are underlain by Precambrian to Lower Paleozoic crystalline Basement rocks and the entire area falls within the southwestern Nigerian Basement Complex (Rahaman 1989). Radiometric dating indicates that the Basement rocks of soouthwestern Nigeria is polycyclic and has responded to several tectonic events with differing intensities from Archean to late Proterozoic (Pan African). Prominent structural trends (faulting and folding) have been observed in this region (Oyawoye 1972, Cooray 1974, Rahaman 1989). Due to the crystalline nature of the rock types in this area, the porosity and permeability necessary for groundwater occurrence are generally lacking. However, appreciable porosity and permeability may have developed through fracturing and weathering processes.

Available data from the United Nations International Children Education Funds (UNICEF)-water assisted projects have shown that borehole in Offa area are designed to tap water from the weathered zone aquifer or the jointed/fractured basement rock aquifer. The boreholes are either singled–screened or multiple-screened, and sometimes open wells are drilled through fractured basement rocks yielding substantial amount of water for private stakeholders. Records from available boreholes show the total borehole depth of between 25.0 to 68.2 metres while overburden thickness varies from 3 - 24 metres. Hence yields of boreholes are generally low, ranging from 0.3 to 2.53 L/s (with a mean value of 1.94 L/s). These values are consistent with an average yield of 0.4 L/s and borehole depth of 40-80 metres estimated for the crystalline basement rocks in Nigeria (Oteze 1983). Yields of between 1-2 L/s in the Nigerian Basement rocks are considered good enough for the installation of motorised submersible pumps while values of borehole yield below 1 L/s are adequate for hand pumps (Offodile 1992).

METHODS

In accordance with the objectives of the study initiated in Offa area, instantaneous information have been gathered from shallow regolith/fractured bedrock aquifers as well as long-term monitoring of water levels and chemistry between 1999 and the year 2002. For the purpose of the present study several hand-dug wells and some boreholes (tapping groundwater at relatively deeper level) have been sampled for chemistry and stable isotopes. The hand-dug wells are in most cases tapping the uppermost regoliths aquifer. Temperature, pH and electrical conductivity (EC) were measured in the filed using portable (battery-operated) meters. Alkalinity test (as $CaCO_3$) was conducted in each of the wells sampled by titration methods using standard field titration kits supplied by Merck GmbH (Germany).

The field results were checked and further laboratory analysis carried out at the Department of Geology, technical University Darmstadt (Germany) by methods of Atomic Absorption Spectrometry (AAS) and High Pressure liquid Chromatography (HPLC). Parameters determined by AAS are Na, K, Ca, Mg (with detection limit: 0.1 mg/L; relative error: 3.5%) while HPLC was used for the determination of Cl, SO_4, NO_3, F, Br (detection limit: 2 mg/L; relative error: 7.5%).

RESULTS

Analytical results of major ions show that water samples are low in Total Dissolved Solids (TDS), mostly below 1,000 mg/L. Hence the water is classified as fresh although elevated concentrations of NO_3 and HCO_3 above the maximum permissible limits in drinking water (WHO 1994) are observed in some places. Water temperature varies from 19.5 to 26.5 ºC. The mean temperature of groundwater is 23.6 ºC while rainwater was measured as 19.6 ºC. pH range is from 6.3 - 7.9 while electrical conductivity (EC) is between 84 to 1013 µS/cm for groundwater. However, rainwater sampled in Offa has a pH of 6.1 and EC as 34 µS/cm.

The predominant anions concentrations are in the order $HCO_3 > Cl > SO_4$ and $HCO_3 > SO_4 > Cl$ for groundwater and surface water respectively while that of cation concentrations are Ca > Na > Mg and Na > Ca > Mg. The details of hydrochemical facies classification in the study area have been discussed in Egbelehulu (2003). The main water type in the area is essentially $CaHCO_3$ with the exception of three samples (FF 12, FF15 and FF23) that shows Na-Cl water type. However, in all the cases, the average concentration of $Ca^{2+} + Mg^{2+}$ exceed that of $Na^+ + K^+$ (fig.1). This water type is a reflection of the predominant rock type in the investigated area where pegmatites (highly prone to weathering) are common intrusions in the gneissic rocks of the area (Olasehinde 1979).

Groundwater isotopic signature shows a range from - 19.2 to 0.8 ‰ for $\delta^{2}H$ (with mean of - 13.7 ‰) and - 3.6 to 3.5 ‰ for $\delta^{18}O$(mean: - 2.2 ‰) as against rainwater ($\delta^{2}H$: 0.8 ‰, $\delta^{18}O$: - 1.0 ‰). A plot of $\delta^{2}H$ against $\delta^{18}O$ show that the isotopic composition of Offa groundwater cluster closely around the Mean Meteoric Water Line (fig.2) defined by the equation:

$$\delta^{2}H = 8.6\,\delta^{18}O + 10$$

with majority of the samples having deuterium excess less than 10. This indicates similar recharge conditions and that could be mainly from precipitation.

The low deuterium excess in the groundwater of the study area was also interpreted as indicating probable enrichment by evaporarion. However, there is much variation in the isotopic content of rainwater in Ilorin (45 Km NW of the study area), perhaps due to altitude and effect. The determination of the altitude effect of atmospheric precipitation is a useful tool for the identification of groundwater recharge zones, as well as for identifying groundwater origin and the dynamics of flow in the area of investigation. This, we hope, will be achieved in the nearest future as more data on stable isotopes in the area become available.

REFERENCES

Cooray P.G (1974) Classification of charnockitic rocks of Nigeria. J Mining Geol 14:1-16

Egbelehulu BE (2003) Hydrochemical evaluation of groundwater in Offa, Southwestern Nigeria. Unpublished B.Sc. thesis, Geology Department, University of Ilorin, Nigeria

Johnson SA (2000) Quality of underground water in Offa, Kwara State, Nigeria. Unpublished B.Sc. thesis, Geology Department, University of Ilorin, Nigeria

Offodile ME (1992) An approach to ground water study and development in Nigeria. Mecon, Jos, 247 pp

Olasehinde PI (1979) Geophysical investigation for groundwater for groundwater sources for Oyun Breweries, Offa, SW Nigeria. Unpublished Technical report, Kwara State Water Corporation, Ilorin, Nigeria

Oteze GE (1983) Groundwater levels and ground movements. In: Ola SA (eds) Tropical soils of Nigeria in engineering practise, Balkema, Rotterdam, pp 39-58

Oyawoye MO (1972) The basement complex of Nigeria. In: Dessauvagie TFJ, Whiteman AJ (eds) African geology, University of Ibadan, pp 66-102

Oyetakin ON (2000) Geology and hydrogeology of Offa, SW Nigeria. Unpublished B.Sc. thesis, Geology Department, University of Ilorin, Nigeria

Rahaman MA (1989) Review of the basement geology of southwestern Nigeria. In: Kogbe CA (eds) Geology of Nigeria, 2nd edition, Elizabethan Publ., Jos, pp 39-56

Shonibare SF (2000) A construction of the groundwater flow direction and trilinear diagram of the perched aquifer in Offa and Ijagbo area, SW Nigeria. Unpublished B.Sc. thesis, Geology Department, University of Ilorin, Nigeria

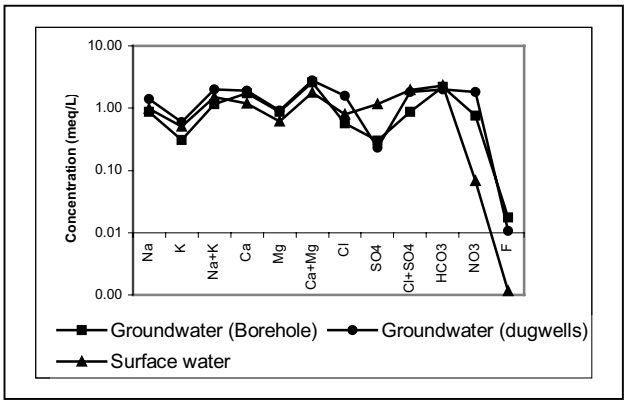

Figure 1. Average equivalent concentration of of major ions and ionic combinations

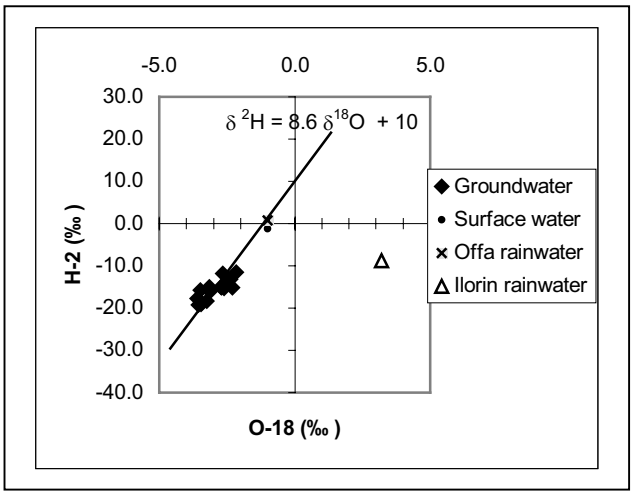

Figure 2. The isotopic composition of Offa groundwater

Variable aquifer quality characteristics in the crystalline basement terrains in parts of southern Ghana

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A b s t r a c t : Aquifer systems in the crystalline basement terrains in parts of the coastal zone of the Central Region of Southern Ghana are characterized by variable water qualities. These range from as low as 200µS/cm to high values in excess of 5000 µS/cm, exceeding the national acceptable limit of 2500µS/cm. Within close proximities of each other (100m or less in some cases) most of the groundwater systems are characterized by different electrical conductivities. These different characteristics exhibited in the different groundwater system have been chemically and isotopically investigated. The various ionic ratio characteristics suggest the mixing of freshwater and subsurface saline formation and/or rock-water interactions are the results of these variable qualities.

INTRODUCTION

The aquifer systems in the crystalline basement terrains in parts of the coastal zone of the Central Region of Southern Ghana are found to be characterized by variable water qualities with electrical conductivity values ranging from as low as 200µS/cm to high values in excess of 5000 µS/cm, greater than the national acceptable limit of 2500µS/cm. Values as high as 10000 µS/cm are also not uncommon. These varying qualities even occur within close proximities (100m or less in some cases) of most of the groundwater systems and show no apparent relationship between the location of occurrence and distance from the coast. These different characteristics in the different groundwater systems have been investigated with the objective of determining the source(s) of the high conductivities.

METHOD AND RESULTS

The various conductivity values were analysed against such parameters as the depth of the aquifer system, as well as the lithological settings.

Considering the fact that electrical conductivity concentration is proportional to the quantity of dissolved ions present in a solution (Fetter 1994) the various groundwater systems were analysed by determining the total dissolved solids by evaporation. This was followed by more precise analysis of the concentrations of the basic ionic constituents. The water samples for these analyses were collected using the sampling protocol described by Claasen (1982), Barcelona *et al.* (1985) and Gale and Robins (1989). The polyethylene bottles used for the sampling were thoroughly cleaned using concentrated reagent grade of hydrochloric acid and rinsed with distilled and de-ionised water. Filtration of the samples was performed to remove particulate matter using a sartorius polycarbonate filtering apparatus and a 0.45µm cellulose acetate filter membrane. Samples for the cation analysis were acidified with nitric acid to a pH < 2 after filtration (Appelo and Postma 1999). The cations contents were determined by inductively coupled plasma-mass-spectroscopy (ICP-MS) technique. For the anion analyses samples were collected in non-acidified bottles. The chloride and sulphate contents were measured by the ion chromatography technique while alkalinity was determined by titration.

The various chemical data were analysed to determine the respective hydrochemical facies using the Piper diagrams (Piper 1984) as well as percent frequency diagrams (Zubari 1999).

As the dominance of one ion over the other is controlled by ion-exchange processes, e.g. the exchange of Ca^{2+} for Na^{+} or the reverse effect, i.e. Na^{+} for Ca^{2+} the ionic data were therefore analysed using the Scheoller index (Scheoller 1959) to determine the type of ion-exchange process the groundwater system might have undergone.

This was followed by stable isotope analysis of deuterium (^{2}H) and Oxygen (^{16}O) based on the tendency of these to fractionate during some geological process of rock formations and consolidations as well as meteorological processes like precipitation and evaporation. This was aimed at distinguishing between fresh and salt intruded waters.

Conductivity-Aquifer Depth Relationship

The various conductivity-aquifer depth relations indicate that aquifers located at 20m or more above mean sea level generally have the groundwater conductivity values lower than the national acceptable limits. While at elevations lower than 20m the aquifer systems may have either a higher or lower conductivity values.

Conductivity-Lithological Settings

Regarding the various lithological settings in the area which are classified into metavolcanics and metasediments; the large percentage of aquifers located in the metasediment, consisting mainly of phyllites, mica-schists and schists exhibit the characteristically by high electrical conductivity values.

Conductivity-Total Dissolved Solids

A strong linear relationship was observed between the electrical conductivity and the total dissolved solids obtained by (i) evaporation and (ii) total ionic contents; with the constant of proportionality reflecting the water type varying between 0.50 and 0.57.

The Hydrochemical Facies

The basic ionic analyses indicate that most of the groundwater systems are associated with elevated concentrations of sodium, calcium, chloride and sulphate ions, resulting in the groundwater systems dominated by Na-Ca-Cl-SO_4 and Ca-Na-Cl-SO_4 facies.

Molar ratios of chloride to the alkaline and alkaline-earth metals in the various groundwater systems differ from similar ratios from a marine sample from the area. While the ratios of Cl^{-}/Mg^{2+} and Cl^{-}/SO_4^{2-} compare relatively to the marine ratio, therefore suggesting that these species are probably seawater related, the Cl^{-} to Ca^{2+} ratios on the other hand, are far lower than the marine ratio, ruling out possible seawater relation.

The relationship between Cl^{-} and $(Na^{+}+K^{+})$; as well as the ratio of Ca^{2+}/Mg^{2+} in the various groundwater systems together point to the fact that most of the sources of such high electrical conductivities waters might be due to the mixing of fresh water and some other saline formation. The relationship between TDS and $Na^{+}/(Na^{+}+Ca^{2+})$ based on Gibbs' boomerang, (Gibbs 1970) also suggest that the groundwater systems might have acquired their chemistries through rock weathering and dilution processes.

The Scheoller index analysis conducted on the ionic data, indicated both negative and positive indeces, suggesting a cation-anion and base-exchange processes in different groundwater systems in the area.

Stable Isotope Analysis

A plot of the isotopic results of the groundwater together with seawater samples from the Gulf of Guinea (Atlantic Ocean) in relation to the Global Meteoric Water Line (GMWL) after Craig (1961), (fig.1) also shows that there is no relation between the various groundwater systems and possible seawater intrusion.

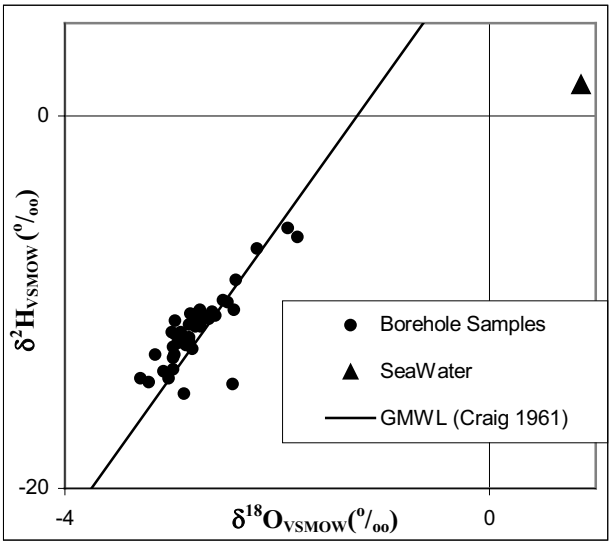

Figure 1. Relation between $\delta^{18}O$ and $\delta^{2}H$ for groundwaters in the study area

CONCLUSION

The results of the various analyses carried on the different groundwater systems indicate variable quality characteristics which show a general reflection in the depth location of the aquifers. The characteristics of the various ionic ratios as well as the stable isotope results indicated that the variable qualities of the groundwaters in the study area might be due to processes involving the mixing of freshwater and subsurface saline formation and/or rock-water interactions.

ACKNOWLEDGEMENTS

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REFERENCES

Appelo CAJ, Postma D (1993) Geochemistry, groundwater and pollution. Balkema, Rotterdam

Barcelona M, Gibb JP, Helfrich JA, Garske EE (1985) Practical guide for groundwater sampling. Illinois State Water Survey ISWS Contract Report 374

Claasen HC (1982) Guidelines and techniques for obtaining water samples that accurately represent the water quality for an aquifer. US Geological Survey Open File Report 82-1024. 49 pp

Craig H (1961) Isotope variations in meteoric water. Science 133:1702-3

Dansgaard W (1964) Stable isotope in precipitation. Tellus, 16:436-468

Gale IN, Robins NS (1989) The sampling and monitoring of groundwater quality. British Geological Survey. Hydrogeology Report No 89/37

Gibbs RJ (1970) Mechanisms controlling world water chemistry. Science 170:1088-1090

Piper AM (1944) A graphic procedure in the geochemical interpretation of water analyses: American Geophysical Union Transaction 25:914-923

Zubari WK (1999) The Dammam aquifer in Baharain – Hydrochemical characterization and alternatives for management of groundwater quality. Hydrogeol J 7:197-208

Submarine springs and salt-water intrusion in fractured environment

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A b s t r a c t : Along the coast of southeastern Sicily, from Augusta to Gela, there are coastal aquifers constituted by carbonate and volcanics rocks. These aquifers are a part of the African foreland, which is knocking against the European plate; they have been fractured intensely with time; this process has given them with a remarkable secondary permeability. The recharge of these aquifers is variable, from zone to zone, but it's generally prominent; the numerous submarine springs of fresh water present along the coast testify to it. Some contrasts between the different directions of groundwater flow in the coastal aquifers above-mentioned have been created owing to the irrational exploitation operated by drilled wells from local inhabitants. In winter there is still a prevalence of the ground water flow from land to sea and the submarine springs are visible and checkable; in summer the excessive withdrawal for irrigational and potable use create drawdown cones of piezometric level which facilitate the seawater intrusion toward the hinterland. The report wish to illustrate and document the current condition and the expedients which have been planned to resist the situation of the present serious deterioration and to try to restore the conditions of an original equilibrium.

The presence of coastal aquifers, constituted by carbonate and volcanic rocks, has been noticed along the coast of southeastern Sicily, from Augusta to Gela. These aquifers are situated in that part of Sicily, called "Hyblaean region", which is a part of the African foreland.

The collision between the African continental plate and the European one causes remarkable tectonic effects in this area; they are characterized by faults that delimit a complex system of horsts and grabens. This phenomenon has affected, in determinant way, the structure of the present aquifers and the relations, which have been established among the same aquifers.

Secondly the tectonic stresses have caused a wide fractured environment which has determined the formation of a secondary permeability in hard rocks (both volcanic and carbonate rocks), promoting a very developed karstification in the carbonate rocks. The meteorological conditions in the past contributed a lot towards the development of the karstification phenomenon; in fact they was marked by precipitation which had been much more abundant than the present ones, marked by annual middle values included between 350 and 650 mm. On the contrary, occurrence of many marly intercalations within the carbonate layers has locally slowed down the development of karstification.

The existence of a very developed hypogeal karstification was testified, until a recent past, by the presence of large springs whose discharge varied considerably during the rainy periods. A lot of springs spouted directly from the sea and was known as "bugli".

Some of these springs, owing to their specific features, have been striking the local people for millennia and the poets and geographers have been making eternal these springs, which are entering in the mythology. The springs called "Ciane" would have been nymphes; also the Aretusa spring, flowing from the small island of Ortigia, situated in front of Syracuse, would has been nymph.

Really the supply of this beautiful spring is due to a fault allowing the reclimbing of the water flow from a aquifer which is confined down the Gulf of Syracuse and unconfined in the Ortigia island (Fig.1).

This description remained unvaried for millennia; the above-mentioned mythoi go back to 2000-3000 years ago, i.e. to the age of the Grecian denomination. Only in the last 50 years the general picture has undergone substantial variations which have upset the local hydrogeologic and hydrochemical structure.

The uncontrolled and impractical exploitation, which has been operated by drilled wells from inhabitants of this zone, has created contrasts between the different directions of groundwater flow in the above-mentioned coastal aquifers.

In addition to the intensive exploitation, even when seasonal, which is practised by local farmers for the irrigation of their lands (on this subject we must consider also a big development of the cultivations in greenhouses on large zones) there is also a remarkable increase of the town planning settlement which has transformed the small fishing villages into blooming tourist-bathing small towns.

In some zones, precisely in Augusta-Priolo-Syracuse and Gela zones, some large petrochemical industries are settled: refineries and chemical products which need much water.

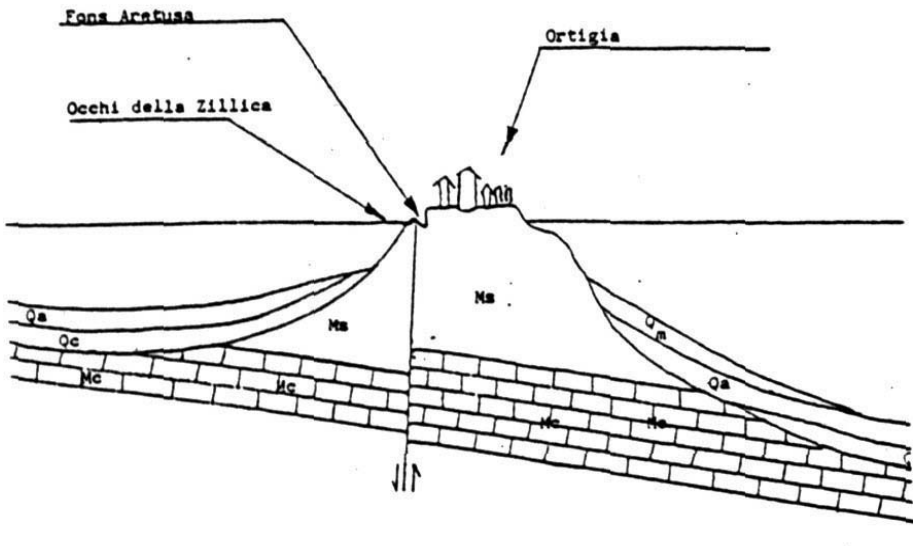

Figure 1. Tectonic scheme of Arethusa fountain at Syracuse (Aureli)

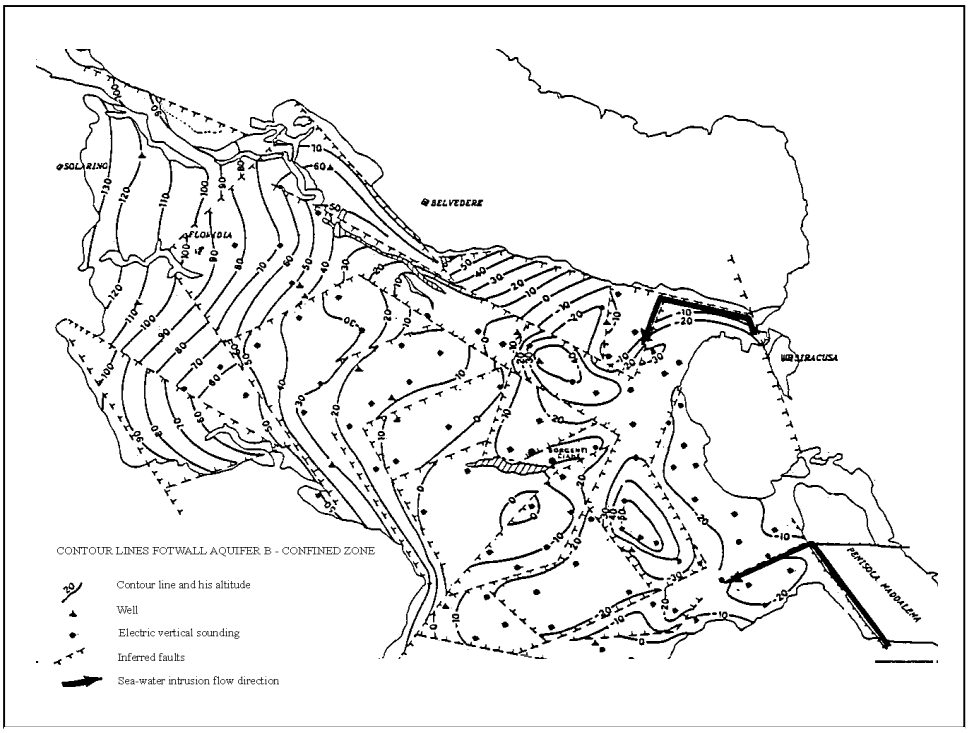

Figure 2. Reconstruction of the roof of the confined aquifer: Zone Ciane (Aureli and Alii 1987)

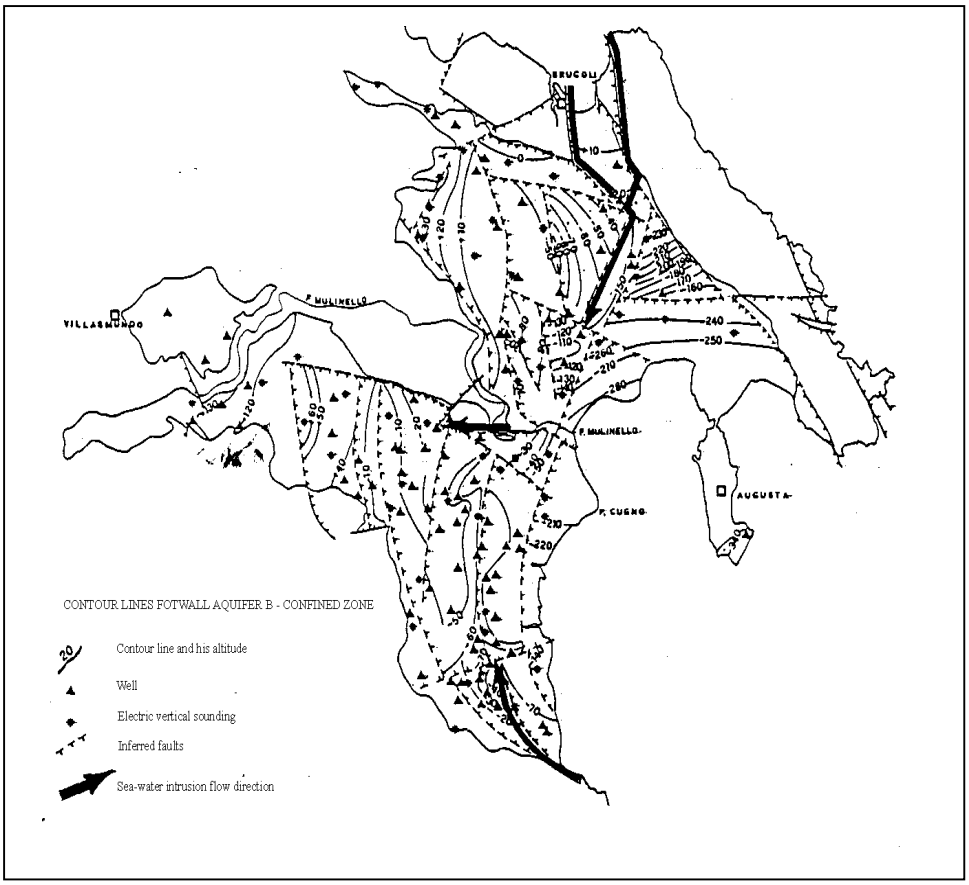

Figure 3. Reconstruction of the roof of the confined aquifer: Zone Augusta (Aureli and Alii 1987)

The uncontrolled and inconsiderate use of the existing wells, exploited irrationally, has caused the depressions of the piezometric level, which in some area has decreased under the sea level (-150 meters). The retreat of the seawater performed by these depressions inverted the flow directions and the salt water, following preferential ways which are defined by existing faults (Figs 2, 3) entered the coastal aquifers, for a lot of kilometers within the shoreline. Moreover, the pollution is added and superimposed to the seawater intrusion.

The pollution can be produced by pesticides and heerbicides, used in the agricultural activity or it can be produced by heavy metals or oil products, due to the dumping or the leakage of them from the reservoirs of the local industry.

The UNESCO, IAEA and Palermo University are financing a research project for the analysis of the above-mentioned phenomena. Moreover, the study of these phenomena consents to plan the interventions, which are considered necessary to stop the current degradation state of the water table and try to restore the original conditions of the underground water flow. In order to do it, some artificial recharge works of the water tables by injection have been planned and partially tested. These works will use the flood water which concentrate in the torrential bed during the winter season and then it will flow into the sea

REFERENCES

Aureli A, Aureli Grifeo A (1986) Salt water intrusion in a coastal aquifer subject to overexploitation an to artificial recharge – 9th Salt Water Intrusion Meeting, Delft maggio 1986 – delft University of technology, 1986, 101-120 pp

Aureli A, Gatti AP, Kholchtchevnikova E, Zanoni M (1987) Projet d'etudes et d'interventions pour la recharge et la protection de l'aquifere cotier dans la plaine de Priolo (Siracuse, Sicile-Italie) – Seminaire sur la protection du sol et des aquiferes contre la pollution de source non ponctuelle, Madrid octobre 1987 – United Nations- Economic Commission for Europe, WATER/SEM.14/R.38, 12 pp

Aureli A (1987) The Augusta's coastal aquifers (Eastern Sicily-Italy) – UNESCO, Groundwater problems in Coastal areas, Studies and reports in Hydrology 45, Paris 1987, 557-565 pp

Aureli A (1994) Esperienze e programmi di intervento in materia di ricarica delle falde, per contrastare l'intrusione marina in un acquifero carbonatico sovrasfruttato – IV Congr. di Geoingegneria "Difesa e valorizzazione del suolo e degli acquiferi – Torino, 10-11 Marzo 1994 3:813-818, Ass. Mineraria Subalpina, Torino

Low mineralized water: challenge for hydrochemical investigations in hard-rock areas

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A b s t r a c t : Generally groundwater in hard rock regions is low mineralized (eC < 120 µS/cm) and of bicarbonate-type. Anthropogenic contamination changes hydrochemical conditions resulting in water of nitrate-, chloride- or sulphate-type with higher mineralization. Despite increased eC-values common quality estimations such as ion balance can not be realized on the usual way because tolerable error ranges are mostly too high. Apart from analytical problems the description of low mineralized waters is influenced by 1) bicarbonate domination, 2) determination of analyzed components near the detection limits of standard analytical methods, 3) low concentrated species and 4) pH-values that are commonly low at the field favoring the influence of dissolved metals.

INTRODUCTION

Major objective of 5th framework EU-project LOWRGREP (Landscape-use Optimisation With Regards of the Groundwater Resources Protection in the mountain hardrock areas) was the provision of data for an optimized water management of water resources in hard-rock areas. The first project phase focused on the description of hydrochemical situation at each test region. All available physico-chemical information and data from field- and measuring campaigns are collected in a data bank system to develop an interactive tool for mutual exchange of experience in water management of mountain regions. First evaluation of data shows predominantly low mineralized water with numerous ion-balances outside quality check criteria.

ION-BALANCE

The common method to check quality of hydrochemical analysis is the comparison of equivalent concentrations of all major anions and cations. According to guidelines of the German association for water management, waste water and waste (DVWK 1979) tolerable errors for low mineralized water range up to 5% (for total mineralization up to 2 mmol (eq)/L). Generally results of hydrochemical investigations made at LOWRGREP-test regions point to good data quality for water with anthropogenic impacts. These samples have an increased mineralization (150-480 µS/cm) and can be classified as nitrate-, chloride- or sulphate-type (Bender 2000, Vornehm *et al*. 2003).

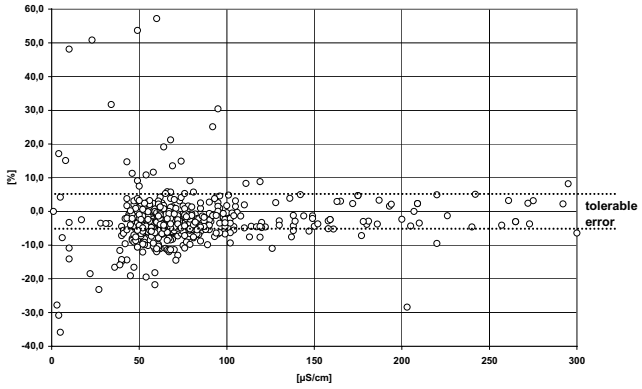

Figure 1. Ion-balance situation in water samples (hard rock areas)

In comparison analysis who did not pass ion-balance check are low mineralized and of bicarbonate-type. An overview of analytical quality as a function of degree of mineralization (fig.1) depicts the higher number of "unbalanced" analysis for samples below 100 µS/cm with a major shift toward a negative balance of equivalent concentrations. Below 50 µS/cm ion-balance strew in a broad spectrum between +80 to –60%. On the first view bicarbonate seems the responsible parameter for most analytical problems due to its predominance in most groundwater with eC-values below 100 µS/cm and its common field screening determination method of titration. Bender and Wohnlich (1998) showed that temporal fluctuations of total mineralization are controlled by major ions, for groundwater in hard rock areas. Due to field titration procedure in combination with concentrations below 40 mg/L analytical confidence intervals range between 15 and 100%, corresponding with 10 to 20% of total negative equivalent concentration. Comparison of two selected water types from the Bavarian Forest (fig.2) show different quality standards for bicarbonate determination in relation to other analytical methods (AAS or IC).

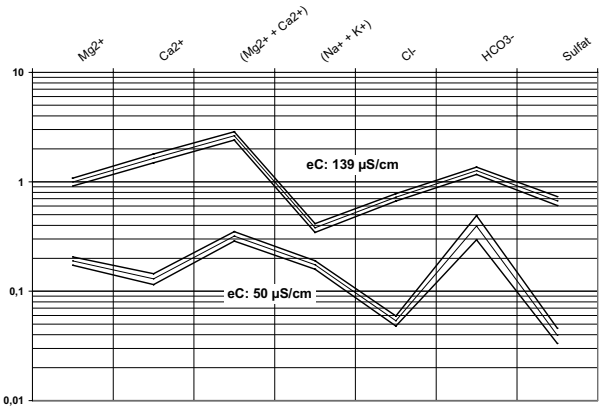

Figure 2. Analytical comparison of two different water types

For water sample (eC=139 µS/cm) tolerance levels for all determined ions are on a same level. But for low mineralized water bicarbonate increase its levels of tolerance. This means that the higher eC-values in hard rock regions are the more accurate are measured bicarbonate concentrations and the lower are probabilities for failed ion-balance checks. It must be pointed out that there are some samples, where bicarbonate is not the source of unbalanced analysis.

SIMULATIONS BASED ON LOW CONCENTRATIONS

Relation between costs and precision of analytical methods is a major factor limiting hydrochemical investigations. Bender and Wohnlich (1997) discussed advantages and disadvantages of standard analytical methods for field investigations. But same problems exist in laboratory, too. Whereas predominant hydro-chemical parameters can be analyzed without problems, most

dissolved species appear at concentration levels near or below detection limit (X_N) of standard procedures. Besides proportionally increased intervals of confidence further problems arise at evaluation of data. Concerning thermodynamic modeling statistic evaluation or using a data base system main interest is: how to treat hydrochemical data below detection limit, where no exact value is available. Jonek and Prinz (1995) listed four different procedures to work with such concentrations (c). Extreme solution methods lie between c=0 and c= X_N. Using the first method all thermodynamic calculations are limited to a lower number of species and phases. Second method overestimates all low values compared to whole data pool. For German LOWRGREP-work the comprise of half amount of detection limit is used to avoid overestimation of fictitious data and to allow thermodynamic calculations based on trace compounds.

The effect of using no or fictive data (different X_N values for Fe_{tot}- and Al_{tot}-content) in a data pool become apparent at calculations using program code PHREEQC (Parkhurst 1995). Using of X_N= 0 results in an exclusion of all species and phases containing this element in output files. No Fe(2)-species were calculated without iron concentrations and Al-S(6)-species appear without a defined A_{ltot}-concentration >0.

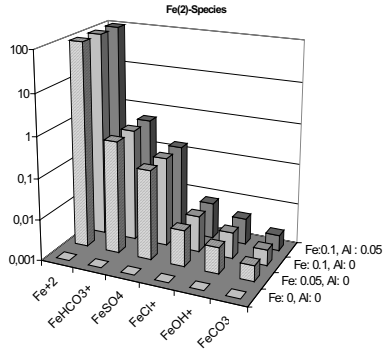

Figure 3. Distribution of "Fe(2)-species" (different X_N-database)

Using option $X_N/2$=0.05 mg/L as hint to dissolved ion traces enables thermodynamic calculations with predominant Fe^{2+} as Fe(II)-species (fig.3) and SO_4^{2-} as predominant S(6)-species. Results using one fictive cation concentration below X_N show no effect on species-distribution for same master species (fig.3) but variations for saturation conditions of appropriate cation-mineral-phases. Higher influences appear with two or more trace elements at species distributions, where aquatic complexes of these species are possible. Fig.4 depicts calculated results using Fe_{tot} and Al_{tot} in different concentrations. Adding a new species to input file enables additional potential aquatic complexes in species-distribution, here: $[FeSO_4]_{aq}$ and $[AlSO_4]^+_{aq}$. Due to addition of a second or multiple trace elements sequence of distribution parts can change dramatically. This effect is shown in the thermodynamic position of $[AlSO_4]^+_{aq}$ regarding the S(6)-species.

CONCLUSION

Estimation of data quality defining hydrogeological situation in regions with low mineralized water is controlled by 1) field determination method of predominant dissolved anion bicarbonate and 2) the number of dissolved cations and anions with concentrations near detection limits. Usage of more accurate analytical methods for determination of lower concentrations is accompanied with higher financial efforts as a result of enhanced analytical disturbances from aquatic phases, which are normally unproblematic in present of higher concentrated ions. So the tool "ion balance", which should be used to control quality of data can not be used according to recent guidelines. Due to sensitivity of low mineralized system small changes can cause high proportional effects.

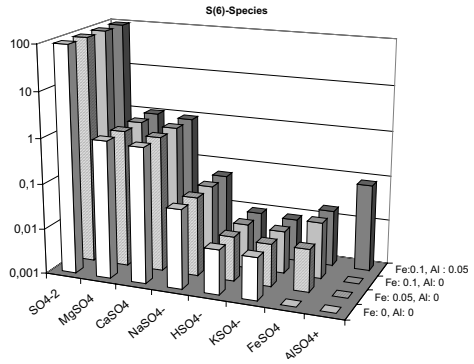

Figure 4. Distribution of "S(6)-species" (different X_N- database)

Working with data below detection limits provokes problems due to fictive information in data pool. The more fictive data were used, the less is the expression of results. For evaluation of information it must be weighted, which results can be used to describe a system and where are limits of available information content.

ACKNOWLEDGEMENTS

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REFERENCES

Bender S, Wohnlich S (1997) Combination Method of Field and Laboratory Measurements for Hydrochemical Field Mapping. In: Gottlieb J, Hötzl H, Huck K, Niessner R (eds) Field Screening Europe, Proc 1st Int. Conf on Strategies and Techniques for Investigation and Monitoring of Contaminated Sites, 235-238

Bender S, Wohnlich S (1998) Temporal variations of physico-chemical parameters in the catchment of the springsystems of Rötz (Upper Palatinate). In: Annau R, Bender S, Wohnlich S (eds) Proc Hard Rock Hydrogeology of the Bohemian Massif. Münchner Geol Hefte B8:57-62

Bender S (2000) Klassifikation und genetische Entwicklung der Grundwässer im Kristallin der Oberpfalz/Bayern. Münchener Geol Hefte B10, 219 pp

DVWK (1979) Empfehlungen zu Umfang, Inhalt und Genauigkeitsanforderungen bei chemischen Grundwasseruntersuchungen. DVWK-Regeln zur Wasserwirtschaft, Heft 111 6pp

Jonek M, Prinz R (1995) Nutzungs- und raumspezifische Hintergrundgehalte organischer Schadstoffe in Böden. Wasser & Boden 11:28-42

Parkhurst DL (1995) User`s Guide to PHREEQC – A Computer Program for Specification, Reaction-path, Advective-transport, and Inverse Geochemical Calculations. Water-Resources Investigations Report 95-4227:143pp

Vornehm Ch, Bender S, Wohnlich S (2003) Geochemical zoning of soil and groundwater due to atmospheric deposition. Proc Diffuse Input of Chemicals into Soil and Groundwater. Assessment & Management, 161-170

Possibility of seawater intrusion in the Ulsan area, South Korea

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A b s t r a c t : A study was carried out on the possibility of seawater intrusion in the Ulsan area, South Korea using 174 analysed groundwater data. Maximum Cl concentration of 11,300 mg/L was detected near downstream of the Taehwa River, wheareas east coast of the study area, composed of granite, showed relatively low Cl concentration. Br/Cl weight ratios from 74 groundwaters ranging from 16.1 x 10^{-4} to 1,292.1 x 10^{-4}, indicating that most of the groundwater is influenced by anthropogenic contamination. To compare the relationship of major ionic ratios of groundwater to seawater, 11 groundwater samples with chloride concentrations greater than 500 mg/L were selected. Except for Na, K, Cl, Br, major ionic ratios of the 11 groundwater was different from that of seawater. The molar ratios of Na/Cl, Ca/Cl, Mg/Cl, and SO_4/Cl of 11 groundwater ranging 0.35 ~ 2.08, 0.001 ~ 0.20, 0.001 ~ 0.22, 0.07 ~ 0.26, respectively. It appears that the origin of the high Cl concentration occurring along the Taehwa River is from the old saltwater accumulated in the river deposits having existed before the development of the city.

INTRODUCTION

The importance of groundwater resources is steadily increasing by shortage and contamination of surface water due to economic growth. Accordingly, there have been concerns about prevention on the groundwater resources depletion and contamination in the country.

The study area is located in the southeastern part of Korea peninsula and densely populated. Therefore, it is anticipated that a possibility of seawater intrusion exists. It is already reported that maximum Cl concentration of 11,300 mg/L from the groundwater near the Taehwa River (KIGAM 2002) in the study area. The aim of this study is to access the origin of the saline groundwater occurring in the study area using Br/Cl weight ratio and major ionic ratios of groundwater and seawater.

HYDROGEOLOGICAL SETTINGS AND SAMPLING

The area is characterized by low relief in the central southern part and relatively steep relief in the north-eastern part. The main river, the Taehwa River, flows from the west to the east entering the Ulsan bay. The main tributary of the Taehwa River is the Dongchun stream. The stream flows from the north to the south and reaches the Taehwa River. The maximum thickness of alluvium around the joining area is 53.2 m (KIGAM 2002). Most of the area is composed of Cretaceous sedimentary rocks and granite.

The city was began to develop from the flat area where the stream joins the river. Before development of the city, the flat area around the Taehwa River was used as saltworks, marsh, and abandoned land. The population of the study area was about 800,000 in 2002. The main inflows to the area are precipitation and leakage from drinking water network and sewer. The average rainfall over the past 30 years is 1,275 mm/y (KIGAM 2002). The known leakage rate of drinking water network is 14% and that of sewer is not known. The main outflows from the area are pumping from the boreholes. The registered borehole number in the study area in 2000 is 1,991 and the accessed total abstraction rate is 31,760 m^3/d (Ministry of Construction and Transportation, 2002).

Total 173 groundwaters were sampled during the dry period (April to May) of 2002 to decrease mixing effects of rainwater. At field, groundwater samples were collected at least five to ten minutes of pumping to evacuate more than three to five times of the borehole storage (Barcelona *et al.* 1985). Samples were filtered in the field with a hand-held syringe using 0.45 μm membrane filters. All sampling bottles were washed with de-ionized water and again with filtered sample waters. The KIGAM laboratories performed major and minor ion analysis. One seawater, and seven river water samples were also collected to be compared with the groundwater quality (Fig.1).

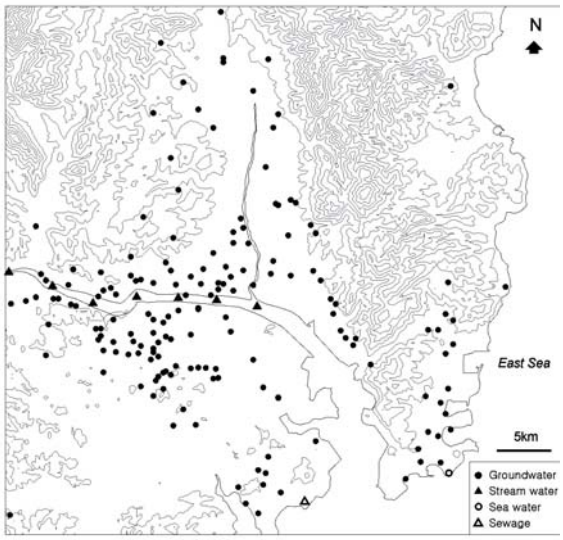

Figure 1. Location map of the sampled water

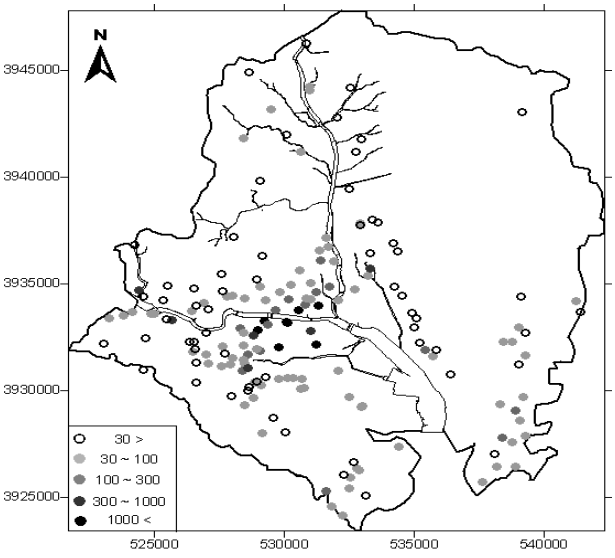

Figure 2. Distribution of Cl concentrations(mg/L) from the groundwater

Table 1. General statistics of the chemical analysis according to water sources

Unit: mg/L

	Groundwater (n=171)				Taehwa river (n=7)				Seawater[1)]	Seawater[2)]	Sewer[3)]
	Range	Mean	Med.	Std. Dev.	Range	Mean	Med.	Std. Dev.			
T (□)	14.6-24.4	17.8	17.3	1.7	17.2-19.0	18.0	18.1	0.7	-	-	21.2
pH	4.60-8.57	6.93	7.00	0.68	6.70-7.11	6.95	6.95	0.15	-	7.96	7.43
EC(μS/cm)	100-31,360	1,198	489	3,680	284-1,150	508	450	300	-	50,700	6,250
K	0.3-164.0	5.8	2.13	16.0	4.0-11.8	6.2	5.6	2.7	380	440	36.4
Na	6.7-5,900	150.6	30.6	574.4	21.0-157.0	53.5	42.5	47.6	10,500	9,850	706
Ca	0.5-1,650	55.4	36.1	135.0	21.6-27.9	24.1	23.6	2.0	400	364	439
Mg	0.4-1,010	33.2	10.8	108.5	3.8-20.7	8.0	6.9	5.9	1,300	1,180	115
Br	0.0-48.0	1.1	0.0	5.5	0.0-0.78	0.18	0.12	0.3	65	71	3.99
F	0.0-3.88	0.23	0.09	0.44	0.25-0.30	0.27	0.26	0.0	1.3	0.1	0.52
Cl	5.1-11,300	286.9	36.4	1,315.5	37.2-264.0	94.3	76.0	80.3	19,000	20,150	1,690
SO_4	0.1-765.0	42.1	25.1	73.7	26.3-61.8	37.0	36.8	11.7	2,650	2,730	575
HCO_3	21.6-1,310.0	216.1	170	176.9	38.7-70.0	58.8	62.6	172.1	140	134	166.2
NO_3	21.6-101.0	12.1	3.9	18.9	9.5-158	11.7	11.4	2.0	-	0.1	3.88
Br/Cl($x10^{-4}$)[4)]	0.0-1,292.1	25.9	0.0	102.0	0.0-29.5	11.6	15.8	11.7	34.2	35.3	23.6

1) Hem, 1992., 2) Seuldo lighthouse, 3) Youngyeon sewage treatment, 4) weight ratio ($\times 10^{-4}$)

BROMIDE :CHLORIDE RATIOS IN GROUNDWATER

Although the use of Br:Cl ratios is obviously not a general panacea for all intractable questions in hydrogeology (Davis *et al.* 1998), bromide and chloride are good indicators because both ions are chemically conservative in natural aqueous environments (Fetter 1993). Similar Br:Cl ratios in groundwater and seawater would indicate that the seawater is the source of the chloride. Dissimilar ratios in groundwater and seawater would indicate that the chloride is derived, at least in part, from another chloride source.

The average chloride and bromide concentrations in seawater are 19,000 mg/L and 65 mg/L, respectively (Hem 1992). Chloride and bromide concentrations in seawater sampled at easternmost are 20,150 mg/L and 71 mg/L, showing slightly higher than the average contents of seawater. The chloride concentration from 173 groundwater ranges between 5.1 and 11,300 mg/L (Tab.1). The high chloride contents were found in the flat area around the Taehwa River (Fig.2).

The Br:Cl ratios and corresponding Cl concentrations from the 74 groundwater having Br contents more than 0.08 mg/L and seawater are plotted in Fig.3. Br:Cl ratios are highly variable where chloride concentration is less than 100 mg/L, implying that the groundwater is highly influenced by anthropogenic source of Br and Cl. Groundwater having Cl concentrations of 100 to 500 mg/L were plotted below the line of $34.7x10^{-4}$, mainly influenced by leakage of sewage water (Vengosh and Pankratov 1998). Groundwater having Cl concentrations more than 500 mg/L also deviates from the known seawater Br:Cl ratio of $34.7x10^{-4}$. Therefore, even though a part of the area is located near coast and reported Cl contents are as high as 11,300 mg/L, it appears that the high Cl in groundwater was not directly influenced by seawater.

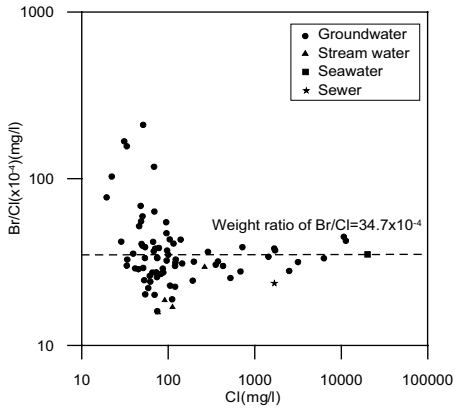

Figure 3. Br:Cl versus Cl concentrations of the sampled water

MAJOR IONIC RATIO OF THE GROUNDWATER

Major ionic ratio of 11 groundwater samples having more than 500 mg/L was compared with that of seawater. Except for the ratios of Cl, Br, Na, K, the ratios of remaining components of the groundwater are different from that of seawater even though they have Cl concentrations of more than 500 mg/L (Fig.4).

The molar ratios of Na/Cl, Ca/Cl, Mg/Cl, and SO_4/Cl of the 11 groundwaters are highly variable and deviating from those of seawater. They rang between 0.35-2.08, 0.001-0.20, 0.001-0.22 and 0.07-0.26, respectively. Accordingly, it appears that the origin of the high Cl concentrations occurring along the Taehwa River is from the old saltwater accumulated in the river deposits having existed before the development of the city.

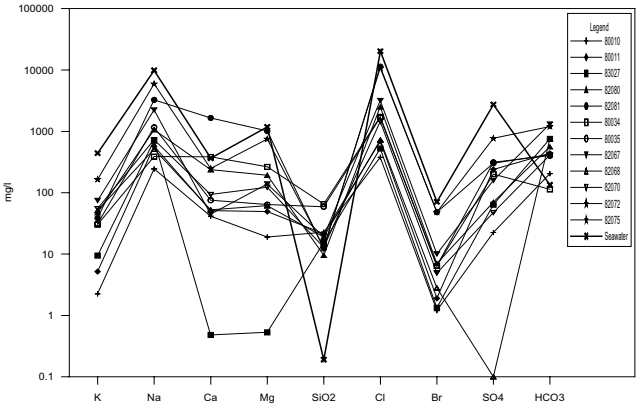

Figure 4. Major ionic concentrations of the 11 groundwater

REFERENCES

Barcelona MJ, Gibb JP, Helfrich JA, Garske EE (1985) Practical guide for groundwater sampling, EPA, 94pp

Davis SN, Wittemore DO, Martin JF (1998) Use of chloride/bromide ratios in studies of portable water. Groundwater 36:338-350

Fetter CW (1993) Contaminant hydrogeology, New York, Macmillan Publishing Co., 458pp

Hem JD (1992) Study and interpretation of the chemical characteristics of natural water (3rd ed.): U.S. Geological Survey water-Supply Paper 2254, 263pp

KIGAM (2002) Study on the groundwater remediation in the Ulsan area, KR-02-06, 123pp

Ministry of Construction and Transfortation (2002) Groundwater survey in 2002, 882pp

Vengosh A, Pankratov I (1998) Chloride/bromide and chloride and fluoride ratios of domestic sewage effluents and associated contamited groundwater. Groundwater 36:815-824

Temperature in the Geothermal Euganean Basin: a Simulated Annealing Aproach

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A b s t r a c t : In the geothermal Euganean area (Veneto region, NE Italy) water temperatures range from 60°C to 86°C. The aquifer considered is rocky, principally extended in fractured Mesozoic limestone. For exploitation purposes, it is important to identify zones with a high probability that the temperature is higer than 80°C. First, variographic analysis was conducted from 186 data temperatures of thermal groundwaters. Then the indicator variogram at the cutoff of 80°C was analyzed. Finally, the locations of areas with a high probability of the temperature being above 80°C were identified by geostatistical simulations of spatial distribution of temperature. In order to perform simulations we use a simulated annealing procedure.

INTRODUCTION

The hydrothermal Euganean area extends on a plain band of about 20 km^2 immediately east of the Euganean Hills (Fig.1), comprising the territories of Abano Terme, Montegrotto Terme, Battaglia Terme and Galzignano Terme. In this area about 100 mining claims and more than 400 wells have been drilled. At present about 250 wells are active and the total average flow rate of thermal fluids in Abano and Montegrotto is about 0.1-0.2 m^3/s. The Euganean aquifer is rocky and confined.

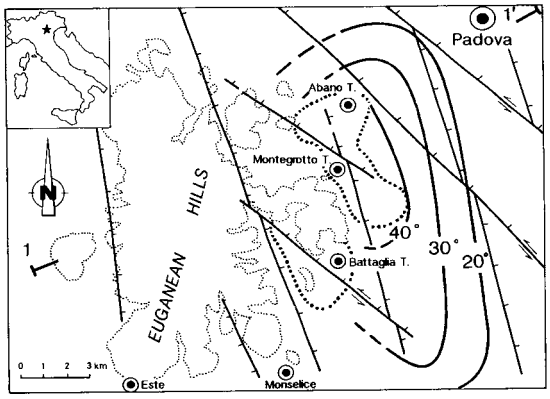

Figure 1. Structural situation of geothermal area (from Antonelli *et al.* 1995)

Most of these exploitation wells extend for several hundred meters into bedrock, however, well casing is only placed in the quaternary cover. The well depths range from about 300 m to more than 1000 m. Wells 1000 m in depth have recently been drilled in the Abano zone.

The temperature of thermal waters ranges from 60° to 86°C, and their T.D.S. is approximately 6 g/L with a primary presence of Cl and Na (70%) and secondary of SO_4 , Ca, Mg, HCO_3, SiO_2.

A conceptual model of the Euganean geothermal basin was first presented by Piccoli *et al.* (1973) and it has recently been confirmed by Dal Piaz *et al.* (1994). This geothermal system has its recharge zone located in the pre-Alpine area (Piccole Dolomiti), where meteoric waters infiltrate at about 1500 m a.s.l. reaching a depth of more than 3000 m, where they are thermalized by a normal geothermal gradient. From this recharge zone the waters descend south-eastwards for roughly 80-100 km until reaching the Abano and Montegrotto areas. Recent studies now in progress regarding the residence time of the Euganean fluids and water samples of the Euganean geothermal field for ^{14}C AMS and tritium measurements, indicate a residence time of much more than 60 years (Sartori *et al.* 1997).

In the Euganean geothermal area the fluids naturally rise by favorable tectonic conditions (Fig.1). Particularly, in the Abano and Montegrotto fields, the fluids rise from localized deep fracture zones. Moreover, when a relatively shallow high fractured carbonatic reservoir (of about 300-500 m) is achieved a horizontal hot water movement is allowed. The thermal fluids are partially stored inside this known fractured reservoir and partially rise again into the alluvial cover until some 10 m from the surface, eventually mixing with the cold water present in the quaternary cover. In fig.2 a geological cross-section of the geothermal Euganean area is reconstructed by geological, structural, lithostratigraphic knowledge, and by geophysical investigations in the subsoil between the Euganean Hills and the city of Padova. The structural situation is connected with the activity of the extensional tectonics controlled by different fault systems of regional importance, the "Schio-Vicenza" being the most significant one.

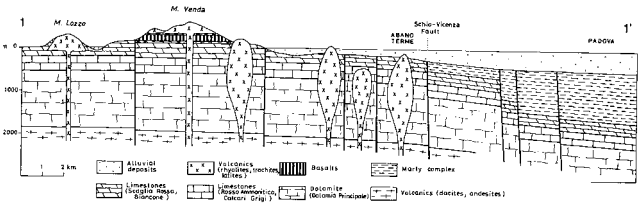

Figure 2. Cross-section of geothermal area (from Antonelli *et al.*, 1995)

The analysis of the piezometric data indicates two periods (spring and autumn) of intense exploitation and two (winter and summer) of low exploitation. At present the level is, on average, about 7-10 m in depth. The comparison between the water level in the deeper and more recently drilled wells and in the other wells (300-500 m in depth) shows a very different piezometric level, but the piezometric variation of artesian wells is in agreement with the seasonal artificial variation (due to exploitation), showing a hydraulic connection between different aquifer zones. Thus all the wells are thought to produce water from different levels of the same thermal aquifer. The water level differences are linked to the high exploitation of the shallower carbonatic reservoir, essentially located in the "Biancone" fm, and to its modest transmissivity (generally ranging from 13 m^2/day to 500 m^2/day) (Fabbri 1997). A similar hydraulic connection was identified in the sandy aquifer at about 60 m in depth in the quaternary cover (Antonelli *et al.* 1995). In fact, its piezometric level has the same regime as the rocky aquifer, but it is only a few meters below the surface. Thus, it is possible to affirm that all the different productive levels in the geothermal aquifer from depths of 60 to 1000 m are locally interconnected and the piezometric difference is related only to the unequal exploitation of different water bearings of the same aquifer.

DATA AND VARIOGRAPHIC ANALYSIS

The 186 data of temperatures considered in this paper concern only the shallower carbonatic reservoir ranging from 300 to 500 m in depth.

In performing the geostatistical analysis the GSLIB Library (Deutsch and Journel 1998) and Variowin codes (Pannatier 1996) are used. First we perform an initial exploratory spatial data analysis, evaluating the summary statistics and the principal

spatial characteristics. The clustering of samples suggests using declustiring techniques in order to have a more representative set of summary statistics. Then the study continues with the analysis of the continuity structure. Variogram cloud analysis (Ploner 1999) does not evidence the presence of outliers and allows for a decision as to which lag distance should be used to study the directional variograms. The study of directional and surface variograms shows that the continuity structure is anisotropic and can be summarized as follows. We see a middle scale anisotropic structure (anisotropy ratio of 0.6) with principal direction along 290° and a large scale anistropic structure (ratio 0.2) with principal direction along 340°. Identification of a large scale anisotropy is very interesting because it is related to an important regional geological structure represented by the "Schio-Vicenza" fault system (Fig.1). This fault system has a direction of roughly 340°. Then indicative variograms of three statistical characteristic thresholds of univariate temperature distribution are studied (second, fifth and eighth decile). Their comparison indicates that higher temperature values are less connected in space than lower ones. This suggests taking in to account the indicative variogram of the economically important threshold of 80°C. The next step is the inference process. This is required in the case of the simulated annealing procedure because we need a theoretical variogram which exhaustively describes the data's continuity structure. This inference process is conducted for the experimental variogram but also for the experimental indicative variogram of the threshold of 80 °C. The experimental variogram of temperature is fitted with a nested model composed of a nugget effect and two anisotropic spherical models. The indicator variogram of the 80°C threshold is fitted by a nugget effect and an anisotropic exponential variogram.

After the variogram analysis and the inference process, the geostatistical simulation of temperature in the geothermal Euganean area is performed.

RESULTS

The objective of conditional geostatistical simulation is to produce a set of equiprobable realizations honoring data values and some desired properties. From the analysis of these realizations we can compute spatial and local uncertainty about the phenomenon being studied. Due to the inconsistency of the multigaussian hypothesis we decide to use a simulated annealing method. This technique is not really a simulation procedure referring to a random function model but rather an optimization method. Here an initial random stochastic image of spatial distribution of temperature is perturbed until it reaches certain desired properties. In this case the desired or target properties are the inferred histogram, variogram and indicator variogram. **Sasim** code is used in order to perform simulated annealing simulations. 500 simulations of spatial distribution of temperature are made. In general, both the histogram and variograms are well reproduced.

We derive some useful maps by postprocessing the 500 simulations: one map with the probability that the temperature in the geothermal Euganean area exceeds 80°C thresholds; another map showing the "E-type" estimates of temperature and third map showing the spatial distribution of the interquartile range. By analysis of fig.3, zones with very probable high temperatures (more than 80°C) and low interquartile range may be identified.

CONCLUSIONS

In this paper the use of the geostatistical simulation to determine the probability of the temperature being more than 80°C in the geothermal Euganean area is shown. The results of 500 simulated annealing simulations of temperatures in the geothermal Euganean field are postprocessed and discussed. Here the importance of detailed variographic studies focused upon the structural variability analysis and the objective work (e.g. temperature thresholds) is pointed out, the study being approached from a hydrogeological point of view.

Finally the choice of the simulated annealing procedure represents a good "exploitation" of the variogram and statistical analysis.

The maps of the probability of the temperature being more than 80°C and the maps of interquarile range reveal some practical hydrogeological information such as (fig.3):

- the identification of an interesting unexploited zone of high temperature in the Abano field with a high probability and a low interquartile range near the "Menegolli" mining claim.
- the identification of a little exploited zone in the Montegrotto field with a high probability that the temperature is more than 80°C and a low interquartile range.
- the localization of areas between the Abano and the Montegrotto field ("Massaggio", "Antoniana" and "Cecchinato" mining

claims) with a low probability that the temperature is more than 80°C and a low interquartile range.

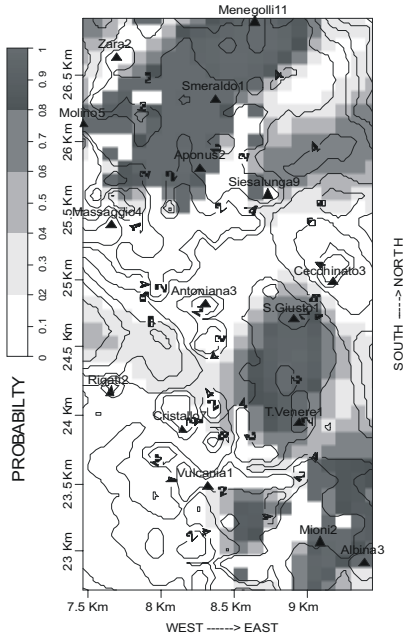

Figure 3. Probability map with superimposed interquartile range (contours)

REFERENCES

Antonelli R, Fabbri P, Iliceto V, Majorana C, Previatello P, Schrefler BA, Sedea R (1995) The hydrothermal Euganean field. A subsidence modelling approach. World Geothermal Congress 18-31 Florence, 1263-1268

Dal Piaz GV, Antonelli R, Bellucci L, Fabbri P, Iliceto V, Noto P, Panichi C, Sedea R (1994) Relazione finale sulle ricerche sul Bacino Termale Euganeo. Final report of research contract Università di Padova – Regione Veneto

Deutsch CV, Journel JV (1998) GSLIB Geostatistical software library and user's guide. Oxford University Press, New York

Fabbri P (1997) Transmissivity in the Euganean Geothermal Basin: a geostatistical analysis. Ground Water 35(5):881-887

Goovaerts P (1997). Geostatistics for natural resource evaluation. Oxford University Press, New York

Pannatier Y (1996) Variowin: software for spatial data analysis in 2D. Springer

Piccoli *et al*..(1973) Contributo alla conoscenza del sistema idrotermale Euganeo-Berico. Atti Acc Naz Lincei, v. XI:103-131, Roma

Ploner A (1999) The use of variogram cloud in geostatistical modeling: Envirometrics, 10, p 413-437

Sartori S, Boaretto E, Fabbri P, Sveinbjornsdottir AE, Heinemeier J (abstract) (1997) 14C content of Euganean geothermal waters (Veneto, Italy). XVI International Radiocarbon conference, Groningen NL

Evidence and constrains revealed by environmental stable isotopes in the chemoautotrophic system of the Movile Cave, Romania

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Abstract: The content of ^{2}H, ^{18}O, ^{13}C, ^{34}S for samples from the area of the studied chemoautotrophic ecosystem provides information about this unusually system. The values of $\delta^{2}H$ and $\delta^{18}O$ from waters of cave area indicate the meteoric origin. The $\delta^{2}H$ average (–85‰) indicates that the most likely recharge area is located at high altitude and its discharge is during summer. The $\delta^{2}H$ spatial variation delineates the areas with vertical inflow and the flowpath of groundwater. The $\delta^{34}S$ from H_2S and SO_4^{2-} presents a contrast trend versus the general trend of the microbially mediated isotopic fractionation. The $\delta^{13}C$ from cave organic matter exhibit low values and reflect not at all the isotopic composition of the local organic materials. The ^{13}C data for CO_2-CH_4 pairs cannot delineate the formation environment (marine or non-marine) of biogenic methane. The $\delta^{2}H$ values of CH_4 correlated with $\delta^{13}C$ values cannot elucidate methanogenesis and the formation environment.

The stable isotopes content of waters collected from study area provided important information about the unusual subterranean ecosystem of Movile Cave that is based on chemoautotrophic conditions. The Movile Cave is closed system, which has groundwater rich in H_2S (8-12 mg/L) and an atmosphere poor in oxygen (7-10%), rich in CO_2 (2-3.5%) and containing significant amount of CH_4 (1-2%). The cave developed into hydrogeologic complex of S-Dobrogea, Romania, and is located near the Mangalia City, only few kilometers far from the Black Sea (fig.1). Climate is semiarid; the land topography is smooth, with low energy. The detritic Palaeozoic formation is overlain by a 450-500m thick stack of mainly carbonate rocks belonging to the Jurassic, the Cretaceous and the Eocene; over them the fosiliferous limestones of Sarmatian age have been deposited in a thickness of 60-150m. 2-30m thick loess deposits covering limestones represent the Quaternary deposits. The loess is actually deposited on a Villafranchian, 2-11 m thick terra rossa shale, of continuous extent. The shoreline is delineated by a 12-18 m high bluff at its bottom Sarmatian limestones outcrop.

Figure 1. The location of Movile Cave.

The tectonic structure indicates the following faults (fig.2): the Kara Oban Fault is orientated on NW-SE direction, sinks toward SE, extends for several kilometres off-shore, across the shelf and intersects the Movile-Aurora Fault in the Mangalia Swamp. 21 thermo-mineral upflow water outlets totalling 210-250 L/s have been identified along its path. These two faults are intersected by a fault orientated by NS lineament, parallel with the seaboard.

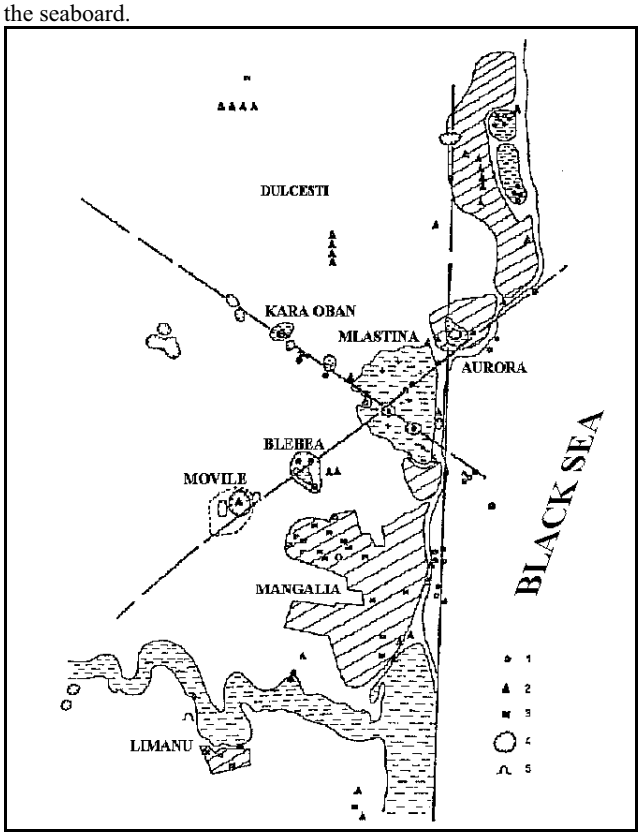

Figure 2. The Mangalia area.

Rocks classified according to their hydrological function include:

➔ The unconfined aquifer in the Sarmatian karstified limestones.

➔ The confined aquifer in the Eocene and Mesozoic limestones, which are fractured and karstified and represent a unitary complex interconnected with upper lying aquifer.

The hydrogen and oxygen isotopes from waters indicates that groundwater in Movile Cave area has meteoric origin.

As a conservative tracer in carbonate rocks deuterium was used to determine the un-elucidated problems of the water origin in cave. The average value of δ^2H for all samples is –85‰, for the most samples (76%) the δ^2H values are lower than -80‰ and is isotopically more light than the waters from the semiarid lowland of the Dobrogea district (over –76‰), indicating that their recharge area is located at high altitude (fig.3). Time series of the deuterium concentration from groundwater samples both from the aquifer in Mesozoic limestone and from the unconfined aquifer in Sarmatian limestone exhibit a distinct seasonal effect and a lower deuterium concentration in summer than in winter. This six-month phase shift of the isotopic composition variations with respect to normal succession of seasonal maximum and minimum values of precipitation and lower δ^2H average values are due to the contribution of the watershed of the more elevated inland (from the Prebalkan Plateau) during summer. The study indicates that the intrusion of water in the karst occurs by conduit flow controlled by the hydrostatic pressure and the geometry of conduit. The interconnection between aquifers is point out by correlation between the δ^2H values and total salinity content. The water of Movile Cave is the result of the mixing of two end members that have different hydrogen isotope ratios. The spatial variation of the deuterium content delineated the areas with vertical inflow and the flow path of groundwater from deep aquifer. The discharge of the deep aquifers occurs through faults and karstic channels into overlying aquifer. The cave and the Kara Oban Lake is the discharge area of two main components of groundwater: the first is coming from southwest and has isotopic characteristic similar to lower altitude water (~500 m) and the second is moving from southeast and has the isotopic composition similar to high altitude water (>1000 m). The Movile Cave and Kara Oban Lake are connected and the cave water discharge by overflow mechanism that offers to cave the isolation of atmosphere.

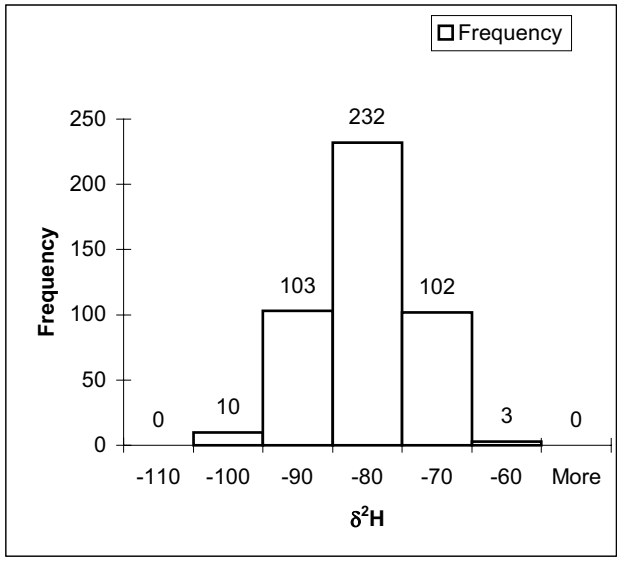

Figure 3. The histogram of δ^2H values.

The ^{13}C content of cave organic matter exhibit low values of $\delta^{13}C$ (between –47.5 and –37.5‰) and reflect not at all the isotopic composition of the local organic materials from surface and subsurface. The concentration of ^{13}C from area vicinal to cave is typically to aquatic and terrestrial communities that use photoautotrophic carbon fixation (between –30 and –23‰). This discrepancy suggests other way of carbon fixation in the trophic web and is possible that the organic matter is derived from organisms more lipid-rich biosynthesized by chemosynthetic microorganisms which use H_2S as energy source for carbon fixation.

Gases collected from the groundwater (H_2S) and the cave atmosphere (CH_4 and CO_2) have isotope ratios that point out the following:

- The groundwater from cave is not originated from Black Sea. The $\delta^{34}S$ values range between +3.5 to +4.2‰ for cave being rich in ^{34}S versus isotopic composition of deep water from Black Sea (-40‰).
- The sulphur isotope content from H_2S (+5.9 to +8.3‰) and SO_4^{2-} (+1.1‰) present a contrast trend versus the general trend of the isotopic fractionation of the microbially mediated sulphur transformations. In cave was not recorded H_2S with $\delta^{34}S$ values lower than that of the SO_4^{2-} reactant.
- The carbon isotope data for CO_2-CH_4 pairs (-23‰ for CO_2 and –56.5‰ for CH_4) of the cave gases cannot clearly delineated the biogenic methane origin as marine or non-marine provenance.
- The equilibrium carbon isotope fractionation between CH_4 and CO_2 is $\alpha_c = 1.35$ indicating that the CO_2 reduction pathway for methanogenesis is very improbable and the natural conditions of the cave approach of the laboratories conditions of the closed system kinetics.

The hydrogen isotope content from CH_4-H_2O pairs (-197‰ for CH_4 and –90‰ for H_2O) cannot clearly differentiate the CO_2 reduction or acetate fermentation as pathway of biogenic methane accumulation in cave. The range in δ^2H values of CH_4 correlated with $\delta^{13}C$ values cannot elucidate methanogenesis and the formation environment (marine or non-marine).

REFERENCES

Craig H (1961) Isotope variations in meteoric waters. Science 133:1702-1703

Feurdean L, Feurdean V, Oraseanu I (2001) The use of deuterium as natural tracer to point out groundwater flow from karst area. Case study. In: Seiler, Wohnlich (eds) New Approaches Characterizing Groundwater Flow:59-63

Sarbu SM, Kane TC, Kinkle BK (1996) A chemoautotrophically based groundwater ecosystem. Science 272:1953-1955

Whiticar MJ, Faber E, Schoell M (1986) Biogenic methane formation in marine and freshwater environments: CO2 reduction vs. acetate fermentation-Isotope evidence. Geochim Cosmochim Acta 50:693-709

Groundwater chemistry related to depth of shallow crystalline bedrock boreholes in Norway

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A b s t r a c t : Data on hydrochemical parameters from 1487 crystalline bedrock boreholes in Norway were divided into subsets according to borehole depth and presented as boxplots. The study shows that there are statistically significant depth-related trends for pH, alkalinity, and the concentrations of Na, F, Mn, NO_3^- and Rn. For Ca, Mg and Si, lower median concentrations are observed in the shallowest borehole subgroup, while no depth-related trends could be discerned for Cl^-, SO_4^{2-}, K, and Fe.

INTRODUCTION

In 1996, a national survey of the chemical quality of groundwater from Palaeozoic and Precambrian crystalline bedrock aquifers in Norway was initiated by the Norwegian Radiation Protection Authority (NRPA) and the Geological Survey of Norway (NGU). This resulted in a data-set comprising quality-controlled samples of groundwater from 1604 bedrock wells and boreholes. All these samples were analysed systematically for pH, alkalinity, radon, 6 anions by ion chromatography (IC) and 30 elements by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Details of analytical techniques are given in Banks *et al*. (1998a,c). The results of this nationwide survey have been disseminated in reports and papers by Banks *et al.* (1998a,b,c), Frengstad *et al.* (2000, 2001) and a doctoral thesis by Frengstad (2002).

Information on borehole depth existed for 1487 of these samples The wells and boreholes were generally relatively shallow, with a median depth of exactly 80 m. Only five boreholes fell within the 180-230 m interval, while the shallowest well recorded was only 2 m deep. The boreholes are typically open-hole for most of their length, with only shallow near-surface casing.

DATA ANALYSIS

In order to evaluate any relationship between borehole depth and borehole water chemistry, boreholes were ranked according to increasing depth and grouped into subsets encompassing 20 m intervals. Boxplots (Tukey 1977) are used to show the distribution of selected groundwater parameters for the different depth subgroups in Figs 1 and 2. In such diagrams, the "box" contains the interquartile (25-75 percentile) range of data, with a horizontal line at the median value. Parentheses above and below the median show a robust 95 % confidence interval for the median. Extraquartile data are shown as "whiskers", with squares/crosses representing "outlying" data.

RESULTS

Although, there is a range of factors affecting both the borehole depth (e.g. actual water demand, available drilling technology, drilling company culture etc.) and the water chemistry (e.g. lithology, intrusion of surficial water due to poor well-head design etc.), several notable correlations were observed.

There was a significant positive correlation between median groundwater pH and borehole depth. Similar correlations were also observed for Na and F^-. For alkalinity, there was a significant increase in median values for depth subgroups down to 60 m, while for larger depths no regular trend could be discerned. These results indicate that deeper boreholes (which tend to have lower normalised yields: yield per drilled metre) tend to draw upon more hydrogeochemically mature groundwater.

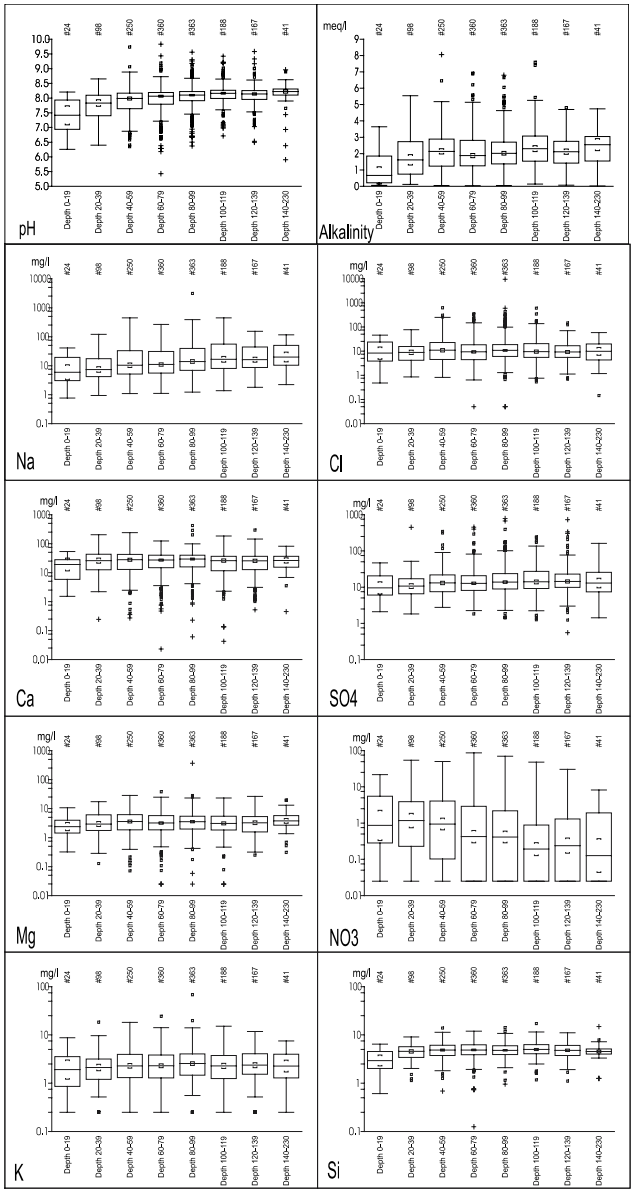

Figure 1. Boxplots showing the distribution of concentrations of pH, alkalinity, major ions (Na, Ca, Mg, K, Cl-, SO4=, NO3-) and Si in groundwater in subgroups sorted according to increasing borehole depth

Ca, Mg, and Si displayed generally lower median values in the 0-19 m subset, indicating immature groundwaters with short residence time in the shallowest boreholes. For larger borehole depths, no significant differences in the median values were observed for these elements. Median NO_3^- concentrations decrease with increasing borehole depth, due to better protection against contamination and a probable tendency towards older water and more reducing conditions with increasing borehole depth. Cl^- and SO_4^{2-} concentrations appeared uncorrelated with borehole depth.

Mn exhibited higher median values in the depth subgroups 40-59 and 60-79 m than in the subgroup 0-19 m, probably reflecting more reducing conditions. The median Fe-concentrations seemed to be rather independent of well depth. In deep boreholes elevated Fe-concentrations may be a result of reducing conditions, while in shallow boreholes Fe may be bound to humic acids in infiltrating surface waters.

The median Rn concentrations for boreholes in the three depth subgroups between 40 and 99 m were significantly higher than the median for the 0-19 m subgroup. For boreholes deeper than 100 m, there was no significant trend in Rn concentrations with depth. Median concentrations of trace elements such as Al, As, Be, Cu, Pb and Zn generally reflected their pH-dependent behaviour in groundwater (Frengstad *et al*. 2001).

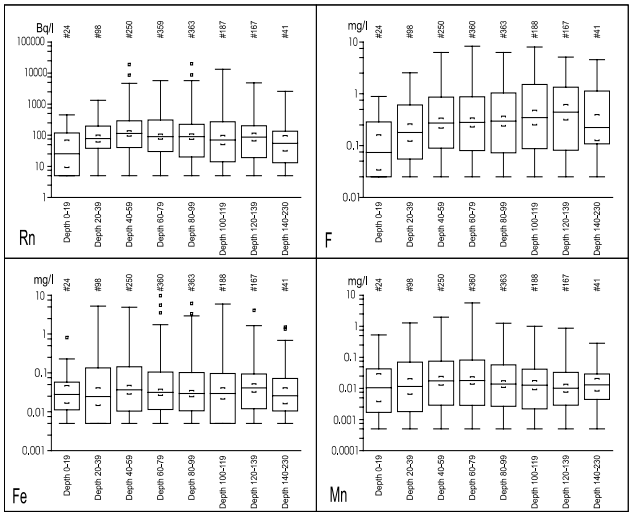

Figure 2. Boxplots showing the distribution of concentrations of Rn (determined by scintillation counting), F- (determined by IC), Fe and Mn (determined by ICP-AES) in groundwater in subgroups sorted according to increasing borehole depth

DISCUSSION

A study of the relationship of groundwater chemistry to borehole depth is *not* the same as a study of the variation of groundwater chemistry with depth. Norwegian hard-rock boreholes are typically unlined for most of their depth. Thus, the water abstracted from a borehole will usually be a mixture of water from a limited number of transmissive fractures at varying depths (Banks 1992). In other words, the water from a very deep borehole *may* be dominantly derived from near-surface transmissive fractures. However, the water from a shallow borehole *must* be derived from shallow fractures and *on average* there is likely to be a greater component of deeper groundwater in deeper boreholes

Rock fractures have a tendency to become less permeable with depth as the stress due to the rock overburden increases (Carlsson and Olsson 1978). It should also be noted that borehole depth is not an independent variable but will be determined by available drilling technology, the drilling company's "culture" and the water demand. If the amount of water required from a borehole is small, there may be a tendency to stop drilling at shallow depths. Conversely, if the water yield is large, drilling may be terminated early. Thus, one might expect to find deeper boreholes in poorly permeable locations and shallower ones, on average, in high yielding situations. Rönkä (1993) showed that the mean yield of Finnish bedrock boreholes of depth 81 - 100 m was less than half the mean yield of boreholes <40 m deep.

Based on these factors it could be argued that shallow wells are more likely to be fed by high-transmissivity fractures than deep ones. The groundwater in such shallow, high transmissivity fractures would also be expected to be less hydrochemically mature.

CONCLUSIONS

A relationship between borehole depth and concentrations of hydrochemical parameters is observed for pH, alkalinity, Na, F, Mn, NO_3^-, and Rn. Ca, Mg, and Si show few depth-related trends, although lower median concentrations in the 0-19 m borehole subgroup are observed. No trends were observed for concentrations of Cl^-, SO_4^{2-}, K, and Fe.

REFERENCES

Banks D (1992) Estimation of apparent transmissivity from capacity-testing of boreholes in bedrock aquifers. Applied Hydrogeology 4:5-19

Banks D, Frengstad B, Midtgård AaK, Krog JR, Strand T (1998a) The chemistry of Norwegian groundwaters. I. The distribution of radon, major and minor elements in 1604 crystalline bedrock groundwaters. The Science of the Total Environment 222:71-91

Banks D, Midtgård AaK, Frengstad B, Krog JR, Strand T (1998b) The chemistry of Norwegian groundwaters. II. The chemistry of 72 groundwaters from Quaternary sedimentary aquifers. The Science of the Total Environment 222:93-105

Banks D, Frengstad B, Krog JR, Midtgård AaK, Strand T, Lind B (1998c) Kjemisk kvalitet av grunnvann i fast fjell i Norge [The chemical quality of groundwater in bedrock in Norway: in Norwegian]. Norges geologiske undersøkelse report 98.058

Carlsson A, Olsson T (1978) Variations of hydraulic conductivity in some Swedish rock types. In: Bergman M (ed.) "Storage in Excavated Rock Caverns", Rockstore '77. Proceedings of the 1st International Symposium, Pergamon Press, New York: 301-307

Frengstad B, Midtgård Skrede AK, Banks D, Krog JR, Siewers U (2000) The chemistry of Norwegian groundwaters: III. The distribution of trace elements in 476 crystalline bedrock groundwaters, as analysed by ICP-MS techniques. The Science of the Total Environment 246:21-40

Frengstad B, Banks D, Siewers U (2001) The chemistry of Norwegian groundwaters: IV. The pH-dependence of element concentrations in crystalline bedrock groundwaters. The Science of the Total Environment 277:101-117

Frengstad B (2002) Groundwater quality of crystalline bedrock aquifers in Norway. Dr. Ing. thesis 2002.53, Dept. of Geology and Mineral Resources Engineering, Norwegian University of Science and Technology, Trondheim. 145 pp + appendices

Rönkä E (1993) Increased depth of drilled wells – advantage or drawback. In: Banks, S.B. & Banks, D. (eds.) "Hydrogeology of Hard Rocks". Memoirs XXIV Congress of the International Association of Hydrogeologists, Ås, Oslo; Norway 28th June-2nd-July 1993, 772-779

Tukey JW (1977) Exploratory data analysis. Addison-Wesley, Reading, 506 pp

Isotope studies of saline groundwater in a sandstone aquifer on Bornholm, Denmark

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A b s t r a c t : Unusally high salinities are recorded in an 118m deep water well in the well field of Nexø Municipal Water Works on the east coast of Bornholm, Denmark. The aquifer lithology consists of quartz cemented and highly fractured ortho- to protoquartzitic Lower Cambrian sandstone resting on Proterozoic crystalline basement. The water body in the studied borehole is significantly stratified with respect to salinity. The groundwater above the halocline reveal hydrochemical and isotopic (^{18}O, ^{2}H and $^{87}Sr/^{86}Sr$) compositions comparable to normal groundwater in the area, whereas groundwater samples from below the halocline show diverging hydrochemical and isotopic signatures. The hydrochemical and isotopic results and ^{14}C dating of depth specified water samples indicate that the saline groundwater has its origin to former intrusion of Holocene (Flandrian) seawater from the high-stand sea level at the Littorine Sea stage (7000-3000a) and subsequently modified by water-rock interaction and mixed with fresh groundwater.

INTRODUCTION

Unusually high salinities (>2000 µS/cm) are recorded in an 118m deep borehole (File No. DGU 247.248) in the well field of Nexø Municipal Water Works on the east coast of Bornholm, Denmark. The occurrence of highly saline water is remarkable for this aquifer, which otherwise yields potable groundwater of good quality (<500 µS/cm).

The aquifer matrix consists of the Nexø Sandstone Formation which is a c. 115m thick uniform red protoquatzitic sandstone, quartz-cemented, with subordinate contents of feldspar. The sandstone is resting on a pre-Cambrian basement comprising granites and gneisses. Primary intergranular porosity is insignificant and the main part of porosity is found in numerous fractures, which are parallel to bedding plane or at steep angles in individual sandstone beds (Skjernaa and Jørgensen 1993).

The current work presents a unique occurrence of saline groundwater in a fractured sandstone aquifer and demonstrates the use of environmental stable isotopes (^{18}O and ^{2}H), and strontium isotope $^{87}Sr/^{86}Sr$ ratios and ^{14}C dating to reveal the origin of enhanced salinity of groundwater.

METHODOLOGY

Electric conductivity logs and electric conductivities of ground water samples and seawater were measured in the field by a WTW Conductivity meter LF 197. Twelve depths specified water samples were collected for oxygen, hydrogen and strontium isotope analyses. The oxygen isotope ratio was determined by acidification with 100% phosphoric acid and equilibration of 5 ml of sample with CO_2 gas as described by Epstein and Mayeda (1953). The analyses were carried out on a VG Sira 10 mass spectrometer with automatic inlet. The water samples for hydrogen isotope analyses were reduced to H_2 by use of zinc in quartz ampoules at 700°C. (Colemann 1982). The analyses were carried out in a Finnigan MAT 250 triple collector mass spectrometer. The results for both isotopes are expressed in per mille (‰) deviation from the VSMOW standard using the δ-scale. Reproducibility is better than 0.1‰ for $\delta^{18}O$ and about 1‰ for $\delta^{2}H$. Strontium for $^{87}Sr/^{86}Sr$ ratio analyses was separated from a 2.5N HCl solution by conventional ion exchange. Approximately 1 µg $SrCl_2$ was mounted on tantalum filaments with phosphoric acid. The Sr isotopic composition was measured on an 8-collector Fisons Sector 54-30 mass spectrometer. Data were collected by multidynamic analysis, and exponential mass-fraction was assumed in the applied correction to a $^{87}Sr/^{86}Sr$ ratio of 0.1194. Within-run precision was typically +/-0.000005 (1 s.d.) on $^{87}Sr/^{86}Sr$ and always better than +/-0.000007. In course of data acquisition, average and reproducibility of measured values of the international standard material NBS987 were $^{87}Sr/^{86}Sr$ = 0.710245 +/-0.000001 (1 s.d.), n=12.

The ^{14}C dating was performed on CO_2 gas expelled from the water samples by acidification with phosphoric acid (McNichol *et al.* 1994). The CO_2 was converted to graphite and dated by accelarator mass spectrometry (AMS) at the tandem accelerator.

RESULTS

Electrical conductivity log

The electric conductivity log reveals a significant stratification of the water body. The groundwater at shallow depth above c. 50m bmp (below measurement point) reveal an electrical conductivity at 400-500 µS/cm which are similar to what generally recorded from other water wells in the study area The depth interval 50-60m bmp appears to be a transitional zone, where conductivity increases abruptly from 500 µS/cm to 1900 µS/cm. The electrical conductivity of the groundwater at greater depth are relatively stable but reveals a slightly increasing tendency with depth and reach a maximum of 2200 µS/cm at the bottom of the well.

Stable isotope (^{2}H and ^{18}O) distributions

The vertical distributions of the stable oxygen and hydrogen isotopes reveal a significant stratification of the water body, which is in accordance with the results of the electric conductivity logs. The groundwater samples show isotopic values that plot slightly above the global meteoric water line (Craig 1961) and reveal two significant groups according to the stratification of the water body. The isotope compositions are relatively constant in groundwater samples above the halocline, i.e. -9.1‰ $\delta^{18}O$ and -61‰ $\delta^{2}H$, which correspond to normal compositions of Danish groundwater (Jørgensen and Holm 1994). The isotopic compositions below the halocline are slightly depleted in comparison to normal Danish groundwater showing $\delta^{18}O$ values at c. -9.7‰ and $\delta^{2}H$ values at c. -65‰. In comparison, the isotopic composition of North Sea seawater are close to normal oceanic composition, whereas Baltic Sea water are significantly isotopically depleted, -9.8‰ $\delta^{18}O$ and -66‰ $\delta^{2}H$, respectively in accordance to the brackish water conditions found in the Baltic Sea (Ehhalt 1969).

Strontium isotope ($^{87}Sr/^{86}Sr$) distributions

The Sr isotope ratios decrease significantly from 0.713 to 0.710 from the top of the water column downwards to 50m bmp at the interface between freshwater and saline groundwater. The Sr isotope ratios are relatively stable but slightly decreasing below the halocline from 0.7100 to 0.7095. The $^{87}Sr/^{86}Sr$ ratios are significantly correlated to the reciprocal Sr contents indicating a mixing line with the isotopic compositions of the freshwater as one end member and the saline groundwater as the other end member.

^{14}C dating

^{14}C dating is performed on 4 water samples collected from above and below the halocline. It appears that two water samples that represent groundwater characterized with relatively low conductivity (<500 µS/cm) reveal increased ^{14}C content relative to the reference year 1950 that indicate groundwater generated in the time interval 1950-1970 during the maximum activity of nuclear bomb testing. However, the water samples of saline groundwater collected below the halocline reveal ^{14}C ages of 2150 BP and 4160 BP at 50m and 92m bmp, respectively. (BP = ^{14}C years before present, i.e. the reference year 1950).

DISCUSSION

The electrical conductivity logs reveal that the water column is significantly stratified with a distinct halocline at approximately 50m bmp. The occurrence of two different water bodies in the borehole is confirmed by hydrochemical investigation and analyses of the stable isotope (^{2}H and ^{18}O) and the Sr isotope distributions in the water column. The water body above the freshwater/saline water interface is isotope-geochemically similar to the compositions of normal groundwater in the study area, whereas the isotopic signatures of the saline groundwater indicate a diverging origin.

The ^{14}C dating of water samples from above the halocline and from other boreholes in the well field reveal relatively young groundwater generated not older than 1950-1970. However, groundwater samples collected below the halocline are found to be significantly older with corrected ^{14}C ages in the range from 2100 to 4200 BP.

The stable isotopic composition of the fresh groundwater above the halocline is remarkable constant and similar to the composition of normal Danish groundwater. The saline groundwater below the halocline shows stable isotope compositions that plot close to the global meteoric water line, but are significantly depleted in comparison to normal groundwater. There is no significant trend in the stable isotopic compositions that may reveal the source of salinity.

The ^{87}Sr/^{86}Sr ratios are relatively high indicating the major source of the Sr is radiogenic Sr released from K-feldspar found the protoquarzitic Nexø Sandstone. The K-feldspar is most likely weathering products and derives from the underlying proterozoic crystalline basement. However, the highest ^{87}Sr/^{86}Sr ratios (0.713) are recorded in water samples collected in the uppermost part of the borehole in contact with the highly fractured and weathered part of the sandstone sequence. The lower ^{87}Sr/^{86}Sr ratios recorded below the halocline may reflect the isotopic composition of the source of the saline groundwater modified by water-rock interaction. Thus, it is worthwhile to note that the Sr isotopic composition of present seawater from the North Sea (0.7092) plots close to the mixing line.

Scattered occurrences of saline groundwater in the Fennoscandian (Baltic) shield have been known since at least the turn of the 20th century. Brackish and saline groundwater has been observed in shallow wells (<200m) drilled into the bedrock of the coastal areas of the Baltic Sea in both Finland and Sweden. These occurrences of saline groundwater are below the highest shorelines of the postglacial Flandrian transgression and have been related in origin to Holocene seawater trapped in the bedrock (Kankainen *et al*. 1987, Nurmi *et al.* 1988).

The high-stand sea level during the Flandrian transgression, the Littorina Sea stage (7000-3000a), lead periodically to salinities close to normal marine conditions in the exterior parts of the Baltic Sea including the Bornholm Basin (Andrén *et al*. 2000). The highest situated shorelines at the east coast of Bornholm representing Littorina deposits are observed 12m above present sea level as a result of postglacial isostatic uplift.

The studied well DGU 247.248 is located below the highest shoreline at 11m above sea level. The ^{14}C-ages recorded for the saline water samples indicate that intruding seawater during the Littorina Sea stage in Holocene (Flandrian) time is the most likely origin of saline groundwater.

CONCLUSIONS

The water column in well DGU 247.248 is significantly stratified showing a freshwater/saline water interface at approximately 50m bmp. The hydrochemical and isotopic results indicate limited interchange across the halocline. ^{14}C-dating indicates that the fresh groundwater is relatively young, most likely infiltrated during the period of maximum of nuclear bomb testing in the 1950-70. In contrast, the saline groundwater shows ^{14}C-ages in the range from 2100 to 4200 BP.

The stable isotopic compositions (^{18}O and ^{2}H) and the distribution of ^{87}Sr/^{86}Sr ratios rule out seawater intrusion from the present day brackish water environment of the Baltic Sea. However, the ^{87}Sr/^{86}Sr ratio distribution may indicate an influence from seawater close to fully oceanic composition. The results suggest that the observed occurrences of saline groundwater below the freshwater/saline water interface has its origin to former intrusion of Holocene (Flandrian) seawater from the high-stand sea level at the Littorina Sea stage (7000-3000a), which has been trapped in the fractured sandstone aquifer and subsequently modified by water-rock interactions and mixed with fresh groundwater.

REFERENCES

Andrén E, Andrén T, Sohlenius G (2000) The Holocene history of the southwestern Baltic Sea as reflected in a sediment core from the Bornholm Basin. Bores 29:233-250

Colemann MP, Shepherd TJ, Durham JJ, Moore GR (1982) Reduction of water with zinc for hydrogen isotope analyses. Anal Chem 54:993-995

Craig H (1961) Isotopic variations in meteoic water. Science 133:1702

Ehhalt DH (1969) On the deuterium-salinity relationship in the Baltic Sea. Tellus 21:429-435

Epstein S, Mayeda T (1953) Variations of 18O content of waters from natural sources. Geochim Cosmochim Acta 4:213-224

Jørgensen NO, Holm PM (1994) Isotope studies (18O, D/H and 87Sr/86Sr) of saline groundwater in Denmark. In: Soveri J, Suokko T (eds) Future Groundwater Resources at Risk. IAHS Publ. 222:231-238

Kankainen T, Kukkonen IT, Lahermo PW, Nurmi PA (1987) Environmental isotope studies on groundwater from the crystalline bedrock in Finland. In: Isotope Techniques in Water Resources Development. In: IAEA, Vienna, Austria. 1987

McNichol AP, Jones GA, Hutton DL, Gagnon AR, Key RM (1994) The rapid preparation of seawater ∑CO2 for radiocarbon analysis at the National Ocean Sciences AMS Facility. Radiocarbon 36(2):237-246

Nurmi PA, Kukkonen IT, Lahermo PW (1988) Geochemistry and origin of saline groundwaters in the Fennoscandian Shield. Applied Geochemistry 3:185-203

Skjernaa L, Jørgensen NO (1993) Azimuthale resistivitetsmålinger – En metode til vurdering af lokale sprækkesystemer i krystalline bjergarter, sandsten og ler (In Danish). ATV-komiteen vedrørende grundvandsforurening. Danmarks Tekniske Højskole, 17 November 1993:1-18

Isotopic study in karst-fractured aquifers: Bohemian Karst, Czech Republic

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A b s t r a c t : The stable isotopes $\delta^{18}O - H_2O$, $\delta^{15}N - NO_3^-$ and ^3H in groundwater were a subject of monitoring in the NW part of the Bohemian Karst, where the largest karst spring is located at Svatý Jan pod Skalou, 25 km SW of Prague. An average spring discharge is about 20 L/s and water has a temperature 11,4 °C. The discharge, temperature, chemical and isotopic composition of the spring water were monitored in 1994 - 1997 period each three days completing by isotopic composition of atmospheric precipitations. Spring outflow was modelled with three components: first component with slow groundwater circulation (approx. residence time of 22 years in the rock environment), second component with residence time of several months and third component with rapid circulation (residence time of several days or weeks).

HYDROGEOLOGICAL SETTINGS

The Bohemian Karst is located in the central part of the Barrandian, which is formed by a discontinuous mosaic of Silurian and Devonian limestones, isolated and interrupted by non-karstic rocks (volcanic and volcanoclastic basaltic rocks, siltstones and shales) and folded into large anticlines and synclines. These structures are affected by transverse faults with vertical and horizontal components of movement. The area of the Bohemian Karst is a hydrogeological structure underlaid by relatively impermeable Ordovician rocks. The Berounka River functions as a local drainage base in its central and SW parts. The main drainage base on its NE margin is the Vltava River.

The spring at Svatý Jan pod Skalou is the largest karst spring resurges in the NW part of the Bohemian Karst (Žák *et al.* 2001). Water issues near the bottom of a 140 m deep canyon of the Kačák Stream. The spring drains SW part of the Holyně-Hostim Syncline formed by volcanic rocks, limestones and siltstones of Silurian and Devonian age. The spring is located at the intersection of tectonic ruptures striking SW-NE and NW-SE to N-S, in the immediate proximity of the local drainage level. An average yield of the spring is ca. 20 L/s.

METHOD USED

The discharge, temperature, chemical and isotopic composition ($\delta^{18}O - H_2O$, $\delta^{15}N$-NO_3^-,^3H) of the spring water were monitored in 1994-1997 period each three days and completed by isotopic composition of atmospheric precipitations. Monitoring was focused on the principal part of the Svatý Jan spring, called Ivanka and Ivan with Q_{min} of 14,1 L/s and $Q_{max.}$ of 29 L/s. The chemical and isotopic composition of nitrogen in nitrates was also investigated in surface water and groundwater in the catchment area of the spring to describe the nitrogen cycle. Binary model according to Horton (1935) was used for evaluation of the share of directly infiltrating precipitations due to a low variability of the $\delta^{18}O$ concentration in spring water and spring discharge. The ratio of the infiltration coefficient for the summer and winter seasons was determined on isotopic composition of oxygen from the precipitations and spring water. The ratio of the infiltration coefficient for the summer and winter seasons based on isotopic composition of oxygen from the precipitations and spring waters according to Grabczak *et al.* (1984) was used for estimation of age of water based on tritium content.

RESULTS AND DISCUSSION

Three components of spring outflow were modelled by the Flow model (Maloszewski and Zuber 1996) and model according to Yurtsever (1983) based on monitoring of the spring discharge, nitrate concentrations and $\delta^{15}N$, $\delta^{18}O$, ^3H isotopic content: first component with slow groundwater circulation (average residence time of 22 years - based on T content), representing 60-70 % of the discharge water, second component with residence time of several months, representing 20-30 % of the discharge water and third a component with rapid circulation (residence time of several days or weeks). It showed up that even though the amount of precipitations in the summer season is two times higher than in the winter one, the amount of water infiltrating in the deep aquifer is for both seasons approximately the same.

The geochemical model revealed that nitrate concentrations in the spring water will increase due to the prevalence of the component of groundwater circulation with an average residence time of 22 years, because water issued in late 1990s was recharged approximately in late 1970s, when nitrate concentrations in the recharging waters were still increasing. Some increase in nitrate concentrations in spring water can be expected by 2005. The decrease in nitrate concentrations in spring water in the future may be hindered by gradual washing of nitrates from a thick pile of weathering products, which fill the indented karst surface in the infiltration area, as well as from the relatively thick unsaturated zone in limestones. The decrease in nitrate concentration in spring water may be also hampered by diffusion of nitrates from immobile water in the karst aquifer into mobile water, or gravity water. Even though nitrogen input in agricultural soil from fertilizers decreased in the Bohemian Karst, increase in nitrogen oxide concentrations (car traffic, gas introduction in local and central heating and gas introduction in large manufacturing plants) and even increase in ammonium concentration in local atmosphere has been registered recently. Current data on nitrate concentration in precipitations on free area range mostly around 4 mg/L NO_3^-, in precipitations under the tree crown between 4 and 10 mg/L NO_3^-, which probably represents one of the factors which influence present significant changes in plant assemblages in forest ecosystems.

CONCLUSIONS

The correlation between maximal spring yield decreasing and time have shown that the dominant circulation regimes of the Holyně-Hostim Syncline are those with laminar groundwater flow with different times of karst aquifer emptying. In these regimes, rocks are deformed mostly by a dense, largely equally spaced network of microfractures and small joints, and water-saturated tectonic zones plays a role of a buffer. Karst permeability takes effect only after heavy precipitation events, being associated particularly with shallow and rapid groundwater circulation with retardation time of several weeks to months.

According to fertilizer application in the recent past, future increase of nitrate content can be expected up to the year 2005. The decrease in nitrate concentrations in spring waters in the

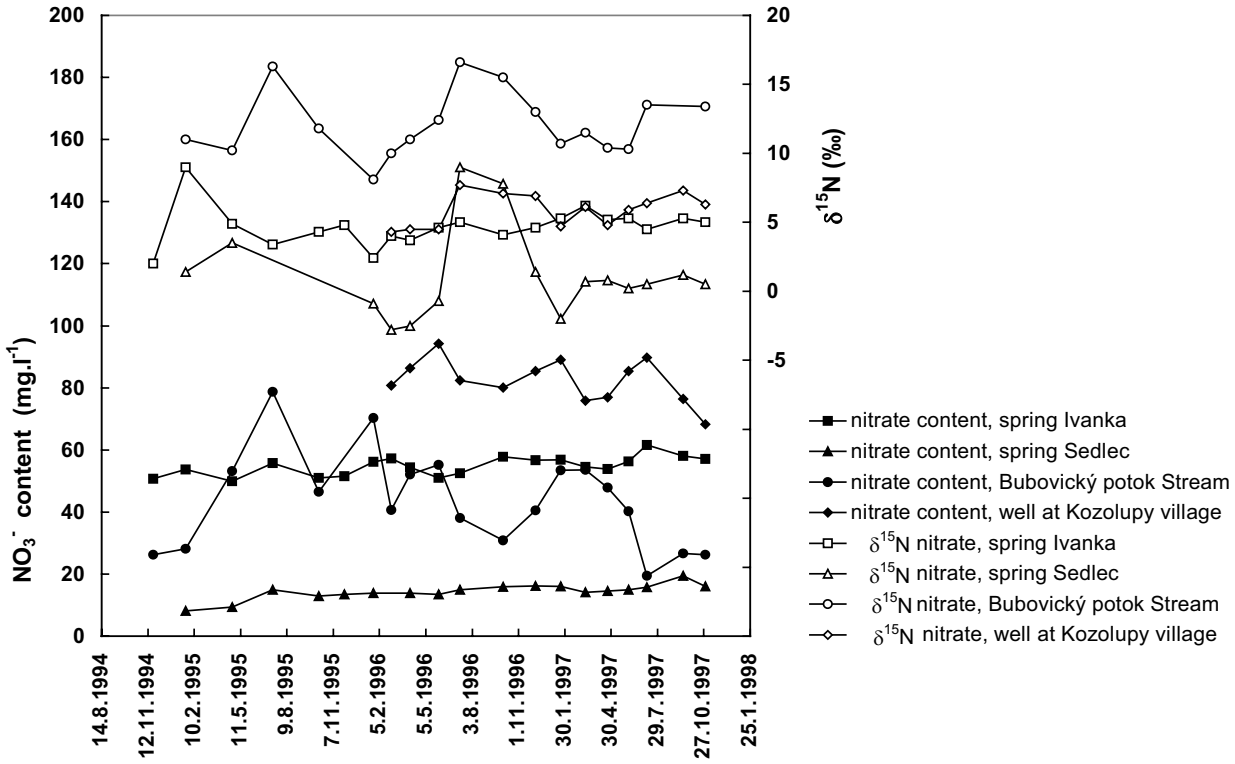

Figure 1. Variations in concentrations of nitrates and isotopes of nitrates in the period 1994 – 1997

future may be hindered by gradual washing of nitrates from soils and weathering products, as well as from the relatively thick unsaturated zone in limestones, by diffusion of nitrates from immobile water in the karst aquifer and increase in nitrogen oxide concentrations (car traffic, emission from local and central heating systems and large manufacturing plants). With respect to all these facts, the real decrease in nitrate concentrations in spring water will be probably much slower than expected by a model calculation considering mobile water only.

REFERENCES

Grabczak J, Maloszewski P, Rozanski K, Zuber A (1984) Estimation of the Tritium Imput Function with the Aid of Stable Isotop Catena 11:105-114. Giesen

Horton RE (1935) The role of infiltration in the hydrological cycle. Transactions Amer. Geophys. Richmond. Union 14:446-460

Maloszewski P, Zuber A (1996) Lumped parameter models for interpretation of environmental trace data. In: Manual in mathematical models in isotope hydrology. Internat. Atomic Energy Agency. Viena. IAEA TECDOC 910:9-59

Yurtsever Y (1983) Models for tracer data analysis. In: Guidebook on Nuclear Techniques in Hydrology, Tech. Rep. Ser. 91 Internat. Atomic Energy Agency. Vienna

Žák K *et al.* (2001) Holocene calcareous tufa accumulation and karstic spring in Svatý Jan pod Skalou (Bohemian Karst). Czech Geological Survey Prague, 136

Quality and vulnerability of groundwater in the Shahrood District, Northeast Iran

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A b s t r a c t : Extensive sampling of three aquifers namely Shahrood (EC: average=2217, min= 480, max= 8700 µS/cm; average pH=7.65; average temp =17°C), Bastam (EC: average=1356, min= 393, max= 3930 µS/cm; average pH=7.63; average temp=14.8°C), and Mojen (EC: average=567, min= 411, max=923 µS/cm; average pH=7.6; average temp=11.6°C) and random sampling of a few other aquifers in the Shahrood District showed 1) an eastward increase in the EC and the temperature of groundwater reflecting the increase in the distance from the Caspian Sea, 2) no substantial trend in the pH, 3) a sharp difference between the EC and the pH of fractured rock aquifers and alluvial aquifers and 4) that the maximum and the minimum EC are 17,100 and 393 µS/cm, respectively. The water table is deep in most aquifers and rainfall is scarce in the district, thus, the risk of groundwater contamination is low. The major threats to the groundwater quality include salt water intrusion, gypsiferous marl formations and excessive use of fertilizers.

INTRODUCTION

Shahrood District in the north-east Iran is a hydrologically arid region where 13 deep aquifers are virtually the sole source of water for the district producing 545 Mm^3 of water per year (Bakhshi 1998). The district is located in the south of the Caspian Sea and forms part of the northern margin and central section of the Kavir Namak Drainage Basin (KNDB), one of the driest drainage basins on the Earth (Fig 1). It is, home to over 200,000 people, 52000 km^2 in area and is regarded as the agricultural centre of the Province of Semnan. District wide, agricultural practices consumes over 95% of the total groundwater produced (Bakhshi 1998). To gain an insight into the quality and vulnerability of groundwater and the governing factors, three aquifers including Shahrood, Bastam and Mojen aquifers were sampled extensively in 2002. On top of 81 samples from these three aquifers, snap shot samples were taken from some other aquifers. Illustrated in Tab.1 are the results of EC, temperature, and pH values as well as the typical chemical analysis from the mentioned three aquifers. For scattered samples, the EC values are shown on Fig.1.

Geologically, a wide range of geological formations crop out in the district ranging from volcanic, metamorphic and sedimentary rocks. Water bearing strata include alluvial fans, flood plains and porous media in general and less extensive are carbonate and other types of fractured rocks. The recharge areas of most aquifers, however, are either carbonate or fractured rocks or both. Of the studied aquifers, Mojen aquifer is an alluvial type one and is surrounded by elevated mountain ranges. Bastam aquifer is composed of a combination of closely located alluvium and carbonate rocks. Similarly, alluvium forms the main water bearing strata of Shahrood Aquifer, but the water is first recharged through carbonate rocks located immediately upstream of the aquifer. In term of land use, Mojen Aquifer is covered by potato farms and Mojen Township. Apricot orchards and Bastam City are the two major land uses over Bastam Aquifer. Similarly, Shahrood City with a population of about 120,000 people and vast grape farms overly Shahrood Aquifer. Generally speaking, water table in nearly all aquifers is deep (100 meters or deeper). This is largely due to great production, and low recharge rates.

DISCUSSION

Referring to Tab.1, samples from Mojen aquifer show the lowest EC values with an average of 567, minimum of 411 and maximum of 923 µS/cm. Similarly, these samples have the lowest temperature values with an average of 11.6°C. In contrast, Shahrood samples with an average EC of 2217 and a maximum of 8700 µS/cm contain the largest salt content. Shahrood samples also show the highest temperature values with an average of 17^0C. Bastam Aquifer, in terms of EC and temperature, falls in between Shahrood and Mojen aquifers. Considering the location of the three aquifers in Fig.1, it is easily concluded that there is an eastward increase in the groundwater EC and groundwater temperature. This is attributed to the fact that the rain bearing clouds originates from the Caspian Sea in the north and northwest and are blocked by the Alborz mountain ranges. In addition, northern and western parts of the district have a mountainous landscape while southern part is mainly a low lying-flat plain with only a small number of scattered mountains. Therefore, rainfall is decreased eastward while the air temperature increases. As a consequence, the quantity of recharged water decreases eastward while its solute content and temperature increases.

Scattered samples collected district wide are highly variable in EC. Their ECs range from 1100 to 17,100 µS/cm. The variation is mainly attributed to the above mentioned factor, i.e. difference in the distance from the Caspian Sea, as well as the effects of local geology. The highest EC is from a shallow bore that was dug to be used for animal feeding, but failed because of excessive salinity of the water. The bore is located 25 km to the southeast of Shahrood, in an upland tributary of the KNDB, and its salinity is attributed to the effect of local gypsiferous marl formations. An irrigation bore drilled into Bastam aquifer and located 5 km to the north of Shahrood City shows the lowest EC in the district. Although, this bore taps alluvial aquifer but the groundwater is thought to originate from nearby carbonate rock formations. In the southern and eastern ends of the district where harshness of the climate has reduced the human population to almost zero, the groundwater is possibly as saline as seawater. Sampling groundwater from these areas involve risks like animal attack, lost, bog down vehicle, and dehydration.

In contrast to EC, there is no significant trend in the value of pH, with all three aquifers having an average pH of about 7.6. However, carbonate rock samples (Bastam Aquifer, average pH=7.75) have a higher pH than alluvial aquifers. In addition, the average EC of carbonate rock samples (Bastam Aquifer) is 617 µS/cm, much lower than the total average of 1356 µS/cm.

GROUNDWATER VULNERABILITY

In term of pollution and groundwater vulnerability, agricultural activities and some local industries in the northern part of the district, mainly around the Shahrood City, are considered to be the potential threats. The deepness of the water table and the low annual average rainfall (about 150 mm) reduces the risk of antropogenic contamination of groundwater significantly. These two factors, depth to water table and net recharge, are the two most important factors in the DRASTIC system of vulnerability evaluation (Aller 1987). However, extensive application of fertilizers in the capture zone of some aquifers like Mojen will eventually contaminate the groundwater. At present, the concentrations of nitrate and phosphate in the Mojen Aquifer are about 14 and 0.1 mg/L, respectively (Tab.1). Toward the south and west, salt-water intrusion from neighboring Kavir (Kavir is a

term used in Farsi to describe the barren deserts and salt laden playas) and contamination as a result of over-exploitation are the chief issues. The causes of high salinity in the Kavir, Kavir Khartouran for instance (Fig.1), are connate water, high evaporation rate (higher than 4 m in some parts), low rainfall, inadequate drainage due to flatness of the landscape and build up of surface salts through geological times. District wide, groundwater recharge schemes have been designed to enhance the quantity of recharged water and to increase the water in storage. These are hoped to reduce the salt-water intrusion potential and alleviate the overdraft related quality problems (Kazemi *et al*. 2002). Gypsiferous marl formations which are widely distributed in the district especially in the southern parts are the other suppliers of soluble ions to the recharging water.

CONCLUSIONS

Throughout the Shahrood District, there is an eastward increase in the solute content and the temperature of groundwater. This trend shows a significant correlation with the distance from the Caspian Sea, i.e. the longer the distance from the Caspian Sea, the higher the EC and the temperature of groundwater. There is no substantial trend in the value of pH. Groundwater samples collected from carbonate rock aquifers are lower in EC, and higher in pH, than those collected from the neighboring alluvial aquifers. Generally speaking, the contamination risk of groundwater is low, but agricultural activities, salt-water intrusion from nearby Kavir, and wide distribution of gypsiferous marl are the potential danger to groundwater resources.

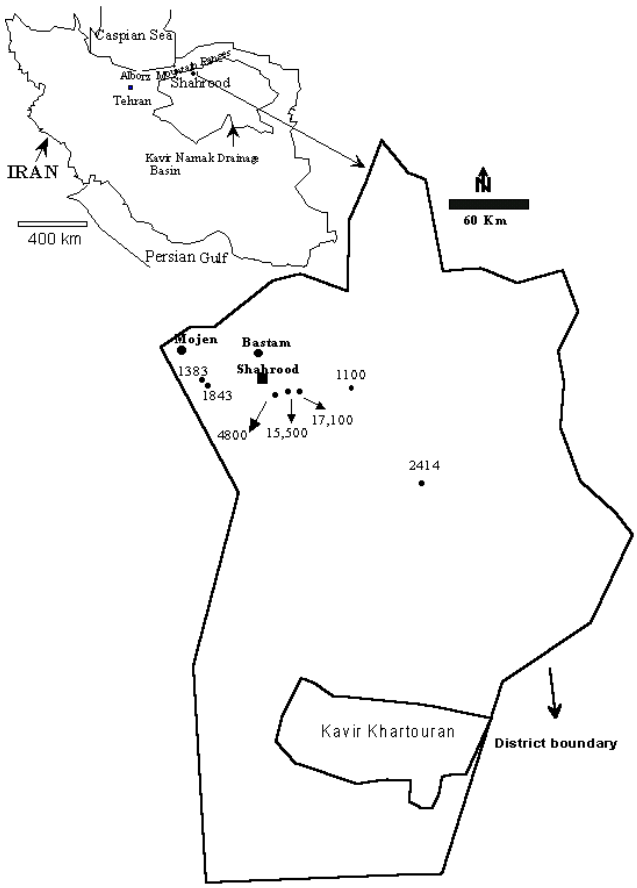

Figure 1. The location of 1) Caspian Sea and Alborz Mountain Ranges, 2) KNDB, 3) Shahrood District in the Northeast Iran, 4) Three studied aquifers, and 5) Kavir Khartouran (an internationally important biosphere). EC values of scattered samples (in µS/cm) are shown in number

Table 1. The value of physical parameters measured during the study and the chemical analysis of the representative samples from the three studied aquifers

Sample	EC	Temp	pH	Sample	EC	Temp	pH
Mojen	528	12.7	7.89	Bastam	919	14	7.81
Mojen	411	10.8	7.67	Bastam	665	14.5	7.94
Mojen	448	9.9	7.48	Bastam	1728	14	7.52
Mojen	510	11	7.6	Bastam	1546	14.5	7.56
Mojen	510	10.5	7.66	Bastam	1676	16	7.44
Mojen	540	12.5	7.79	Bastam	1135	16	7.58
Mojen	530	10.8	7.61	Bastam	1159	17	7.55
Mojen	545	10	7.47	Bastam	1330	16	7.55
Mojen	562	10	7.63	Bastam	2460	14	7.42
Mojen	923	14	7.47	Bastam	1509	16.5	7.62
Mojen	552	9.8	7.48	Bastam	1940	16	7.35
Mojen	557	11	7.54	Bastam	1949	15	7.47
Mojen	533	10	7.51	Bastam*	622	14.3	7.68
Mojen**	623	14	7.49	Bastam*	632	17.5	7.7
Mojen	737	16.6	7.57	Bastam*	618	14.7	7.75
Shahrood	4400	18.8	7.45	Bastam*	613	15.8	7.83
Shahrood	8720	17.5	7.42	Bastam*	598	15	7.75
Shahrood	5260	17.2	7.33	Bastam	606	14	7.95
Shahrood	703	17	7.63	Bastam	393	17.5	7.85
Shahrood	901	18	7.8	Bastam	1232		7.45
Shahrood	1377	14.5	7.74	Bastam	1437		7.56
Shahrood	1030	16.3	7.69	Bastam	1780		
Shahrood	1975	17	7.67	Bastam	1873		7.65
Shahrood	933	18	7.84	Bastam	1524		7.63
Shahrood**	1293	17.3	7.92	Bastam	1970		7.57
Shahrood	1120	17	7.87	Bastam	3930		7.02
Shahrood	2560	16	7.45	Bastam	1511		7.77
Shahrood	2060	16.5	7.67	Bastam	1955		7.73
Shahrood	1650	16.6	7.55	Bastam	1930		7.45
Shahrood	1007	17	7.79	Bastam	1160		7.68
Shahrood*	480			Bastam**	1544		7.74
Bastam	1069	14		Bastam	1785		7.71
Bastam	724	14.5		Bastam	1222		7.36
Bastam	825	14		Bastam	1323		7.58
Bastam	1074	13		Bastam	1671		7.33
Bastam	915	13		Bastam	1953		7.63
Bastam	663	14.3	7.99	Bastam	1719		7.52
Bastam	690	14.8	8.08	Bastam	3200		7.87
Bastam	645	14.9	7.94	Bastam	1264		7.51
Bastam	656	14.2	8.06	Bastam	1704		
Bastam	593	14.9	8.03				

EC:µS/cm, Temp:^{0}C *: samples from carbonate rocks aquifer
** Samples analyzed in the laboratory for major ions as follow:

Sample	K^+	Na^+	Mg^{++}	Ca^{++}	NO_3^-	PO_4^{--}	SO_4^{--}	Cl^-	HCO_3^-
Mojen	2.1	81	17	48	14	0.09	60	63	185
Shahrood		71	62	80			154	188	207
Bastam	4.6	276	39	60	8	0.09	288	175	225

(concentrations in mg/L)

REFERENCES

Aller L, Bennet T, Lehr JH, Petty RJ, Hackett G (1987) DRASTIC: a standardized system for evaluating groundwater pollution potential using hydrogeologic settings. US EPA, Ada, OK, EPA/600/2-87-036, 455pp

Bakhshi M (1998) A short report on the climate, water resources, and solutions for the management of water shortage problems in Shahrood. In Proc of Shahrood and Development Symposium, Shahrood, Iran, pp 143-164

Kazemi GA, Mehdizadeh H, Ashouri R (2002) Evaluation of groundwater recharge schemes in the Shahrood District, Northeast Iran. In: Dillon P (ed) Management of Aquifer Recharge for Sustainability. Proc of the 4th International symposium on artificial recharge, Balkema, pp 225-229

Quality of bedrock groundwater in the communal supply wells of Leppävirta, eastern Finland

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A b s t r a c t : The communal water supply of Leppävirta is based on bedrock groundwater. The concentrations of iron, manganese and radon in water from some of the 8 production wells exceed the recommended maximum values. Geological factors affecting the quality of bedrock groundwater in Leppävirta were examined by utilizing water analyses, pumping data and drill logs. Geological mapping, thin sections of rocks and chemical rock sample analyses were also used for characterizing the geology. Concentrations of ^{222}Rn are highest in waters of wells drilled into granite. The concentrations of Fe are clearly dependent on the oxygen content. The Mn concentrations are high in water of every well and appear to correlate with thickness of the overburden. The decreased extraction volumes possibly indicate depletion of groundwater resources which appears to have an impact on the chemistry as well.

INTRODUCTION

Leppävirta is a municipality of 6000 inhabitants in the North Savo region of eastern Finland about 50 km south of Kuopio. The communal water supply of Leppävirta is based on bedrock groundwater pumped from 8 borehole wells. Leppävirta is the first and only town in Finland to extensively use bedrock groundwater for its water supply, since larger communities in Finland commonly rely on eskers and other glaciofluvial aquifers or surface waters. Due to the lack of significant glaciofluvial formations the municipality, together with the former Water and Environment District of Kuopio and the Geological Survey of Finland (GSF), carried out investigations to assess the area's bedrock groundwater potential. A change in legislation has led to the municipality to carry out more consistent quarterly quality monitoring of the supply wells since the spring of 2001.

Generally, the quality of the water has been good and stable, but in some wells the concentrations of Fe, Mn and ^{222}Rn exceed the recommended limits, and simple treatment is thus required. The recommended values given by the Ministry of Social Affairs and Health and the Radiation and Nuclear Safety Authority for potable water distributed by utilities in Finland are for Fe, Mn and ^{222}Rn 0.2 mg/L, 50 µg/L and 300 Bq/L, respectively.

The composition of bedrock groundwater reflects the rock type, hydrological flow conditions and chemical interactions – which are affected e.g. by redox processes – between water and rock-forming minerals. Fe and Mn are dissolved in groundwater primarily through weathering of mafic silicate minerals and oxidation of sulphides in bedrock and soil, but also through degradation of biogenic matter (Lahermo and Vuorinen 1988). In glaciofluvial aquifers the occurrence of Fe and Mn is principally affected by the O_2 balance of the aquifer, which is dependent on the geological structure and flow pattern (Hatva 1989). ^{222}Rn, which is a member of the uranium-238 radioactive decay series, can be found in high concentrations especially in groundwaters of granite areas. Granitic rocks contain elevated levels of U (Salonen 1994).

The Palaeoproterozoic bedrock of the Leppävirta area consists mainly of synorogenic granites and granodiorites, mica schists, metavolcanic rocks and sulphidic schists. The research area represents the contact region between the Svecofennian schist belt (Savo schists) and the Karelian schist belt. The area is located in a zone affected by a major geotectonic suture known as the Raahe-Ladoga fracture line. The rocks in the Savo schist zone are typically strongly metamorphosed and migmatized. The direction of fracture zones is commonly NW–SE. The mineral soil is predominantly moraine. The 8 supply wells are situated mainly either in the granite or mica schist (gneiss) area, allowing a study of potential differences in water compositions arising from different rock types. The wells are situated in an area of about 20 km^2.

DATA AND METHODS

Since the 1990s, the studies have included pumping tests, water quality analyses and geophysical ground surveying, such as seismic soundings, and interpretation of aerogeophysical data (Breilin 2000). The water quality analyses have not been performed regularly, and the wells and chemical parameters have varied. Since 2000 the analyses have been consistently carried out by the same laboratory: the Varkaus City Food and Environmental Laboratory.

The more detailed present study includes a review of the earlier data such as water analyses, pumping tests and drill log notes. Complementary geological mapping, studying of thin sections of the rocks and chemical rock sample analyses (XRF) were also used to characterize the well environments, allowing comparison with different groundwater quality parameters. Additional water samples were taken and analysed for common quality parameters, using ICP-AES/ICP-MS at the GSF for the main cations, anions and trace elements.

RESULTS

The thin section studies that were restricted to Sorsakoski indicated that the granite in the area is typically porphyritic with microcline, quartz, biotite and plagioclase as the main minerals. Apatite, zircon and opaques occur as accessory minerals. The mica gneisses in Sorsakoski consist of micas, quartz and plagioclase.

^{222}Rn is most clearly dependent on the rock type of the borehole well. The concentrations of ^{222}Rn are highest in the well waters of Sorsakoski (wells S1, S2, S2.3 and S3), where the bedrock consists mainly of granite. In S1 the concentrations have been as high as 900–2900 Bq/L. In the Pohjukansalo mica gneiss area and in Porttila, which is located in the granodiorite area, the concentrations of ^{222}Rn have been lower: 200–370 Bq/L. The U contents of both granite and mica gneiss samples were below the detection limit of 0.001%.

The concentrations of Fe are highest in S3 (mean 2.47 mg/L) and lowest in S1 (mean <0.05 mg/L). The O_2 concentrations are highest in S1 (mean 1.29 mg/L) and lowest in S3 (mean 0.45 mg/L). Consequently, the Fe concentration appears to be dependent on the O_2 content.

The concentrations of Mn are high in all of the well waters in Leppävirta. The highest concentrations occur in Pohjukansalo P1 and P2, where the bedrock is mica gneiss, and in S2, where the bedrock consists mainly of granite but also mica gneiss. The mean concentrations in P1, P2 and S2 are 772 µg/L, 1183 µg/L and 784 µg/L, respectively. With the exception of P2, the Mn concentrations are high in wells with a thick overburden.

The Mn concentrations in Pohjukansalo are currently 4–6 times higher than in the early 1990s during the pumping tests (Fig.1). The Fe concentrations, in contrast, have not varied. The extracted volumes are currently during continuous extraction 3 times smaller than during the pumping tests. Since 1998, after the Pohjukansalo wells were brought into use, the Mn concentrations have increased until 2001, especially in P2. Since 2001 – probably due to low recharge – the extraction volumes have been 30% smaller than in 1998–1999. Continued monitoring will verify whether the Mn concentration will remain at the level to which it has risen.

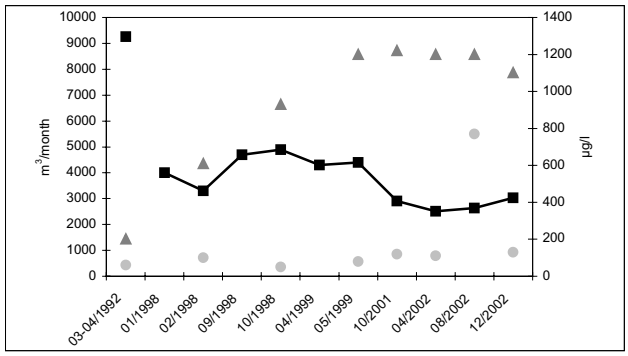

Figure 1. Pumping volumes (■) and Mn (▲) and Fe (●) concentrations in well P2. Note the steps in the time axis

The amounts of the main cations – in particular Ca^{2+} and Mg^{2+} – and SO_4^{2-} are highest in waters pumped from wells bored in mica gneiss. With the exception of the two sulphate-dominated wells in Pohjukansalo, the borehole well waters of Leppävirta are bicarbonate waters, which typically occur in Finland (Fig.2).

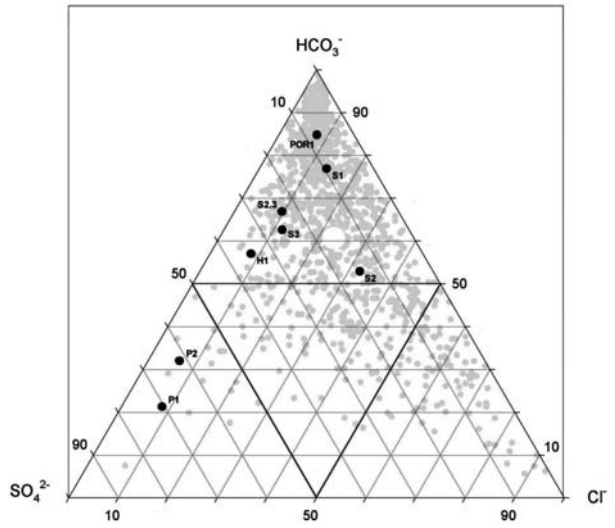

Figure 2. Triangular diagram showing the equivalent percentages of the main anions in borehole well waters of Leppävirta (black) and Finland (gray, Lahermo *et al.* 1990)

DISCUSSION AND CONCLUSIONS

The maximum concentrations of Fe, Mn and ^{222}Rn are 10 times higher in borehole well waters of Leppävirta than the mean values for Finland. Despite the relatively limited number of analyses, certain effects of geological factors can be inferred. The concentrations of ^{222}Rn are most clearly dependent on rock type and are highest in the waters of wells drilled into granite. The Fe contents are strongly dependent on the concentration of O_2 but there was no correlation between the Fe contents and rock type. The thickness of the soil appears to correlate positively with the Mn concentrations, probably by affecting the O_2 balance. However, the O_2 contents do not appear to correlate consistently with the thickness of the overburden. The high concentrations of Ca^{2+}, Mg^{2+} and SO_4^{2-} may have resulted from a higher proportion of more weathering-prone mafic minerals in the gneisses.

The variability of previous quality data, available since the 1990s, complicates the assessment of temporal trends and highlights the significance of consistency in monitoring. Nevertheless, it appears likely that the extraction of groundwater has resulted in a change in water quality. Increasing concentrations of Mn in Pohjukansalo – especially in well P2 – may be a result of decrease in the groundwater resources. Before the pumping tests the aquifers were fully recharged, but during continuous extraction the water resources have diminished and the concentrations have increased until the pumping volume has been reduced. The concentrations of Fe and Mn in P1 have recently decreased but the latest data from December 2002 show that the Fe and Mn contents have again increased after water extraction had been raised. The extraction history of wells in Pohjukansalo is the longest in the area – approximately 10 years – and is therefore most likely to indicate changes, if any. To avoid changes in groundwater quality, extraction in the wells should not exceed sustainable yield.

It appears that the chemistry of the groundwater has changed during the period of utilization. To verify the suspected effects of water extraction, a follow-up investigation of pumping volumes linked with monitoring of groundwater quality and quantity should be carried out over a sufficient length of time.

REFERENCES

Breilin O (2000) Kalliopohjavettä Leppävirran kunnalle (Bedrock groundwater for Leppävirta municipality). In: Salonen V-P (ed) Ympäristögeologian päivät 14.-15.3.2000: suomalainen pohjavesigeologia: ohjelma – tiivistelmät – osallistujat (Environmental geology meeting 14.-15.3.2000: groundwater geology in Finland: programme – abstracts – participants) [in Finnish] Publications of the Department of Quarternary Geology, University of Turku 83:17

Hatva T (1989) Iron and manganese in groundwater in Finland: occurrence in glacifluvial aquifers and removal by biofiltration. Publications of the Water and Environment Research Institute 4. National Board of Waters and the Environment, Helsinki, 99 pp

Lahermo P, Vuorinen A (1988) Geochemistry and biogeochemistry of Fe and Mn in Finnish surface water and groundwater. Chemical Geology 70(1-2):11

Lahermo P, Ilmasti M, Juntunen R, Taka M (1990) The Geochemical Atlas of Finland, part 1: The Hydrogeochemical Mapping of Finnish Groundwater. Geological Survey of Finland, Espoo, 66 pp

Salonen L (1994) U-238 series radionuclides as a source of increased radioactivity in groundwater originating from Finnish bedrock. In: Soveri J, Suokko T (eds) Future groundwater resources at risk: proceedings of an international conference (FGR 94) held at Helsinki, Finland, 13-16 June 1994. IAHS Publication 222:71-84

Salinization of water in fractured chalk (Eocene aquifer, Negev, Israel)

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A b s t r a c t : Salinization processes in the Eocene chalk aquifer in the Negev involve three different media: the porous chalk medium, which contains saline water of sea origin; a medium of fine fractures and one of karstified fractures. The porous chalk medium does not participate in the groundwater flow, though it contributes salts by diffusion to the fractures. A medium of fine fractures does not control the groundwater flow, but defines the salt transport from the porous media to the fractures. Most of the groundwater flow occurs through karstified fractures.

INTRODUCTION

This paper presents the conceptual model of groundwater salinization in fractured chalk aquifer in the Negev, Israel. This conceptual model makes it possible to explain the uncommon phenomena observed in this aquifer, such as: decreasing water levels accompanied by decrease in groundwater salinity, presence of Tritium in ancient sea water trapped in the chalk porous medium, seasonal changes in groundwater chemical composition, etc. This conceptual model has been approved by three numerical models:

a. transport model of porous medium fracture interface;
b. transport model simulate pumping test in the aquifer;
c. flow model via unsaturated zone.

Field observations have been used for models calibration. All hydraulic parameters presented in this article are based on the results of numerical modeling.

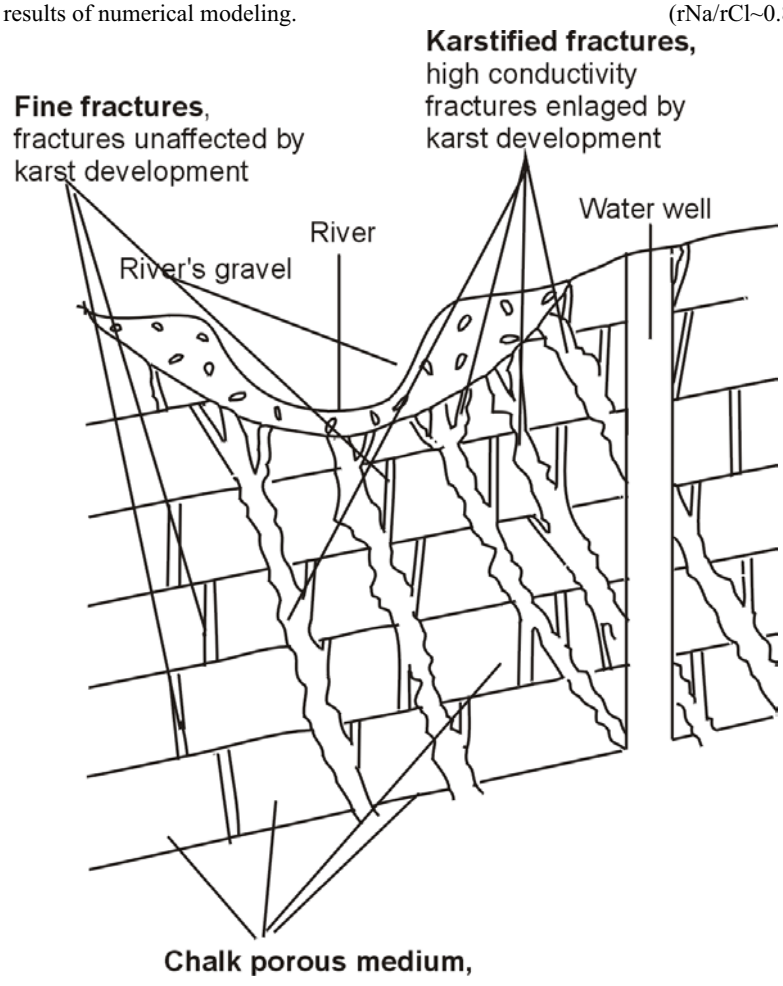

Figure 1. Main fracture systems

GEOLOGICAL SETTING

The Avdat group of the northwestern Negev is composed mainly of fissured Eocene chalk. Two main fracture types systems are recognized in the chalk (Fig.1):

a) Single-layer fractures with openings of one mm and less.

b) Multi-layer fractures with openings of up to several cm. Karstic processes enlarged some fractures, mostly those of the multi-layer group.

WATER CHEMISTRY

The groundwater salinity (TDS) in the aquifer ranges from 600 mg/l up to 10,000 mg/L. Water salinity increases along the flow pass. Water characterized by marine like ratios of major ions (rNa/rCl~0.85; rMg/rCl~0.18 and Cl/Br~300). Same marine like ions ratios and salinity (TDS) up to 30.500 mg/L have been observed in the chalk pore water (pore water has been extracted applying immiscible displacement method).

It was assumed that the main source of this salinity is ancient residual water trapped in the chalk pores

The application of the a quantitative multi-component mixture model revealed that groundwater of the Avdat aquifer has been formed by mixing of fresh rain and floodwater with the chalk's pore water. Pore water contributes less than 10% of the groundwater volume, but contributes more than 70% of groundwater salinity (TDS).

SALINIZATION MODEL

The hydraulic conductivity of the chalk is very low and most of the flow in the aquifer takes place along fractures. The flow and transport processes involve three different media (Fig.2):

The porous chalk medium. Characterized by a very high storage coefficient and extremely low conductivity. This medium does not participate in the groundwater flow, but contributes salts by diffusion to the fractures (mostly to the fine fractures).

A medium of fine fractures (unaffected by karstic development). Each fine fracture is characterized by low hydraulic conductivity (about 10^{-4} m/day). A large number of such fractures defines low conductivity and a high storage coefficient of the fine fractures medium. This medium does not control the groundwater flow, but defines the salt transport from the porous media to the fractures.

A medium of karstified fractures (enlarged by karstic processes). Each karstified fracture is characterized by high hydraulic conductivity (about 100 m/day). However, owing to a relatively small number of karst-affected fractures (about 5% of aquifer volume) the entire medium of karstified fractures has high conductivity and low specific storage.

Most of the groundwater flow is through these karstified fractures.

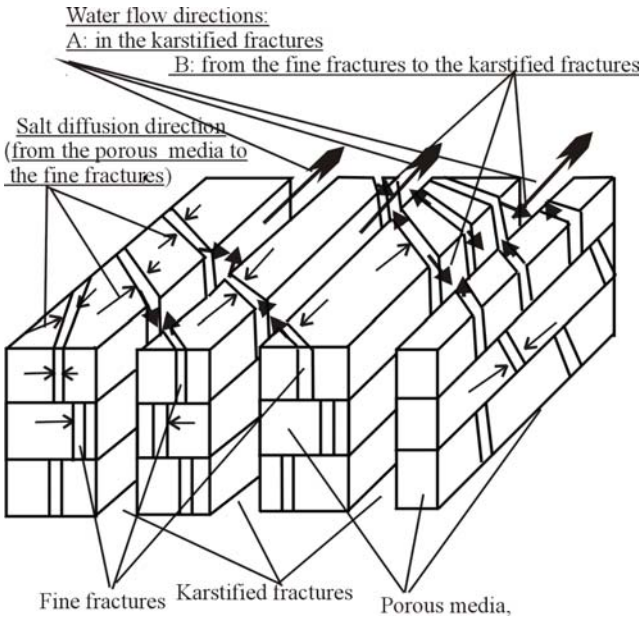

Figure 2. Media involved in flow and transport processes

Characterization of mineral waters of Pedras Salgadas (North Portugal) by statistical methods

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A b s t r a c t : The mineral waters of Pedras Salgadas are located in the North of Portugal in fractured rock formations associated with different types of granites. Their genesis is related to the great fault system of Penacova-Régua-Verin. The mineralisation of these carbonated waters with natural gas ranged from 672 mg/L to 3467 mg/L with values of CO2 ranging from 500 mg/L to 5800 mg/L. The hydrochemical facies is sodium-carbonated. In order to understand the inter-correlations between the main physical-chemical parameters and respective temporal patterns of these waters a set of statistical and multivariate data analysis techniques were used. Data were monitored in 5 observation points: 3 deep wells and 2 springs. More than 20 water quality parameters have been measured since 1986 monthly. The objectives of the study are twofold: to describe a typology of waters taking into account the differences between mineral waters and spring waters by using Principal Component Analysis and to detect the trends and the rate of change of some parameters using Mann-Kendall test.

INTRODUCTION

Portugal is one of the richest E.U. countries in what concerns mineral waters. Vidago-Pedras Salgadas hydro-mineral field situated in North of Portugal is one of the most important Portuguese concession. In spite of the enormous importance of these mineral water resources, there is notwithstanding a great absence of planning and management tools that allow a correct optimisation of the exploitation of the resource. Consequently, there is a growing need to apply adequate tools that permit a proper quantitative and qualitative evaluation of those fluids, being one of the main objectives to analyse correctly the temporal evolution of the main water quality parameters in terms of the magnitude of their trends.

GEOLOGY OF VIDAGO/PEDRAS SALGADAS REGION

The existing carbonated waters in Portugal are located in the north area of the Hesperic Massif, namely in the middle Galiza-Subzone (see fig.1). Their geographical location is well correlated with regional fault systems. They emerge on the granites and schist, usually on the intersection between the great regional faults and their conjugates, because it is normally on these sites that the best conditions for the rising of the fluids from the deep zones of the crust exist. These fluids exhibit at the surface several levels of alteration. The presented carbonated waters are related with the great Penacova-Régua-Verin fault (with a NNE-SSW direction), which is long and deep and affects the entire continentals crust. The carbonated springs occur mainly in the W branch of the fault, and sometimes in their conjugate WNW-ESSE, emerging on areas where the pós-tectonic granitoid rocks are dominant.

Figure 1. Location of Vidago-Pedras Salgadas hydro-mineral field in Portugal

PHYSICAL-CHEMICAL PROPERTIES

The mineral waters of Pedras Salgadas are hypo-thermal, with values below 20ºC They are naturally carbonated, with high content of sodium. Mineralization ranges from 1400 mg/L to 6900 mg/L, pH values between 6 and 7 and free CO_2 between 500 mg/L and 5800 mg/L.

WATER QUALITY DATA

There are 3 deep wells (AC12, AC13 and AC17) and 2 springs (Fte Sabroso and Sabroso Nova Nascente) in Pedras Salgadas concession.

The monitoring program implemented by the Geological Mining Institute since 1986 consists on 3 to 4 simple physical-chemical analyses per year and one complete analysis every 4 or 5 years. For this study a total of 843 observations is available from the period ranging from 1986 to 1996. Each observation consists on information of the following variables: F, CO_2, SiO_2, Cl, HCO_3, SO_4, Na, Mg and Ca. For a first visualisation of the temporal evolution of each parameter the correspondent time series were plotted. Fig.2 shows a downtrend of the parameter HCO_3 detected in AC12 and AC13 wells and also a clear seasonality in the former well.

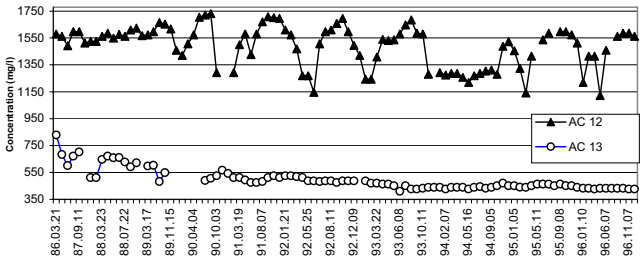

Figure 2. Temporal evolution of HCO3 in AC12 and AC13 wells

PRINCIPAL COMPONENT ANALYSIS

A PCA was applied to a matrix of water quality descriptors of Pedras Salgadas field to analyze the main oppositions and similarities between groups of wells and variables. In Pedras Salgadas field results show (fig.3) that the 1st factorial plan explains a total of 90.65% of the initial variance; HCO_3 ion contributes significantly for the interpretation of the axis 1, linked with the Cl, Ca, Mg, Na and free CO_2. This group of parameters is opposing to F. On the other hand axis 2 is a

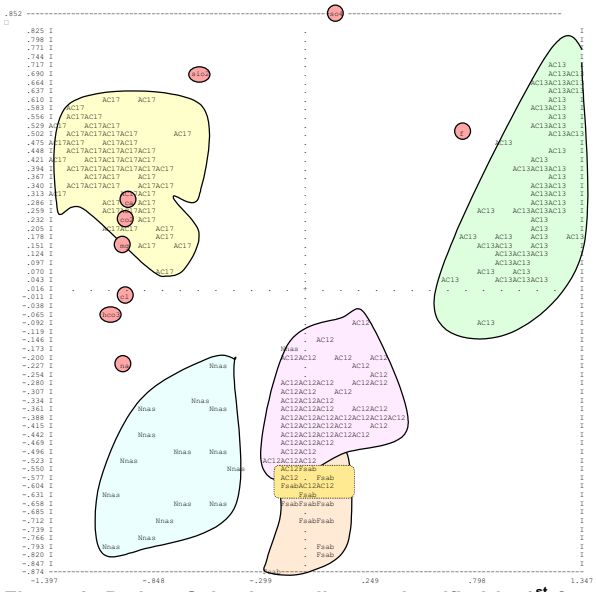

Figure 3. Pedras Salgadas wells are classified in 1st factorial plan

discriminate axis for parameter SO_4. The various wells are clearly individualized in independent groups.

THE MANN-KENDALL TEST

The Mann-Kendall test is a non-parametric statistical method mainly used to detect and assess the trends of the water quality parameters (Hirsch *et al*. 1982). The selection of a non-parametric approach is particularly suitable to analyse data exhibiting one or more of the following properties: free distribution, missing values, presence of outliers, seasonality, censored data.

The test is applied to a sequence of observation ordered by time $q_1, q_2, \ldots, q_n$, where a parameter S is build according to the following expression:

$$S = \sum_{k<j} f\,(q_j - q_k) \qquad (1)$$

Where:

f is a function defined by: $f(\theta) = 1$ (if $\theta > 0$); $f(\theta) = 0$ (if $\theta = 0$) and $f(\theta) = -1$ (if $\theta < 0$)

A null hypothesis H_0 of no trend is tested and rejected or confirmed according to the statistical distribution. To measure the strength of the upward or the downward trend a statistic p is calculated. In general trends are considered statistically significant when $p<0.1$. For this study a seasonal Mann-Kendall test procedure will be used and an estimation of the correspondent slope will be performed by a robust regression suggested by Thiel and Sen.

The slope of the trend is given by the median (B) calculated on the basis of all the values d_{jk} following:

$d_{jk} = (q_j - q_k) / (j - k)$ for all the pairs q_K with $1 \le k < j \le n$ (2)

The trend slope is expressed by change per unit time and is related with S by: If $S>0$ then $B \ge 0$; If $S < 0$ otherwise.

The test can be applied with other techniques in a joint methodology in order to achieve a particular objective (Ribeiro and Macedo 1995).

RESULTS

The non-parametric test was applied to the mineral waters of Pedras Salgadas to the period from January 1986 to December 1996. Monthly observations of the physical-chemical parameters listed above were used for this purpose.

Tab.1 display the results of the detected upward, downward or no trends, the estimated slope (change per year) and the statistical p for Pedras Salgadas field

The analysis of this table shows that AC12 and AC13 present the greatest variability in the detected trends for all the parameters. On the contrary the 2 springs (Fte. Sabroso and Sabroso Nova Nascente) show in general a no trend behaviour. The presence of significant upward and downward trends is perhaps due to the pumping system in those wells that affect the CO_2 and consequently the major and trace composition, specially in HCO_3.The great magnitude of the estimated slopes between wells were found in the observed trends of CO_2, SO_4 and Ca, mainly in the former with an estimated slope of 4 mg/L per year for AC 12 (upward) and AC 13 (downward). The value 16.7 mg/L per year in CO_2 found in AC 17 seems high, however when we compare with the mean values of this parameter and with the total mineralization of this well, we conclude that is lower 0.4%.

Table 1. Water quality trends in Pedras Salgadas

Wells / Parameters	F	CO2	SIO2	Cl	HCO3	SO4	Na	Mg	Ca
AC 12	.000 ⇔ .350	3.976 ↗ .003	.000 ⇔ .970	-.035 ↘ .001	-2.028 ↘ .00	.018 ↗ .001	-.658 ↘ .001	-.033 ↘ .002	-.157 ↘ .001
AC 13	.007 ↗ -.001	-4.167 ↘ -.001	.007 ⇔ 0.815	-.013 ↘ .007	-1.917 ↘ -.003	.058 ↗ -.003	-.511 ↘ -.002	-.012 ↘ .018	-.083 ↘ .001
AC 17	.000 ⇔ .243	16.667 ↗ .00	-.012 ⇔ .375	-.002 ⇔ .388	.153 ⇔ .723	.027 ↗ -.003	.000 ⇔ .887	.025 ↗ .012	.131 ↗ .008
Fte. Sabroso	.125 ↗ .014	1.423 ⇔ .623	.000 ⇔ 1.000	.050 ⇔ .302	.621 ⇔ .259	-.015 ⇔ .192	.545 ⇔ .107	-.033 ⇔ .674	.123 ⇔ .401
Sabroso Nova Nascente	-.005 ⇔ .104	.017 ↗ .053	-.121 ⇔ .496	-.060 ⇔ .495	-9.846 ⇔ .263	-.130 ⇔ .194	-.198 ⇔ .974	-.525 ↘ .027	-1.000 ⇔ .300

legend:

-.002: slope
↗ upward trend ↘ downward trend ⇔ no trend
p:.002

CONCLUSIONS

The temporal evolution of the 9 water quality parameters monitored in 5 wells of the carbonate waters of Pedras Salgadas showed significant upward and downward trends, although the estimated slopes are in general not important taking into account the high mineralization of these waters. The high variability in trends detected in some parameters are closely related to the pumping system, with indirect influences in the fluctuations of the CO_2. Furthermore, in the hydro-mineral field of Pedras Salgadas, only the deep wells displayed a clear variation in the trends of the descriptors.

In further studies influences of exogenous factors such as the pumping rates, well depths and temperature will be considered.

REFERENCES

Hirsch RM, Slack JR, Smith RA (1982) Tecnhiques of Trend Analysis for Monthly Water Quality Data. Water Resources Research 18(1):107-121

Ribeiro L, Macedo ME (1995) Application of Multivariate Statistics, Trend and Cluster Analysis to Groundwater Quality of Tejo and Sado Aquifer, In: International Conference on Groundwater Quality: Remediation and Protection – GQ95, Prague, Czech Republic, IAHS publication nº 225, pp 39-47

Evolution of CO_2-rich mineral waters from Hercynian granitic rocks, North Portugal: questions and answers

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A b s t r a c t : The hot and cold CO_2-rich mineral waters from Vilarelho da Raia, Chaves, Vidago and Pedras Salgadas areas (N-Portugal) have δ^2H and $\delta^{18}O$ values that are similar to those of the local meteoric waters, indicating the meteoric origin of the mineral waters. $\delta^{13}C$ values of CO_2 gas and dissolved inorganic carbon and previously reported $^3He/^4He$ values indicate that the carbon in these CO_2-rich mineral waters is derived from a deep-seated (upper-mantle) source. The low ^{14}C activity measured in some of the CO_2-rich mineral waters is incompatible with the systematic presence of ^3H in those waters, which should be faced as an isotopic signature of a short underground circulation path. Differences in the $^{87}Sr/^{86}Sr$ values presented by the studied thermomineral waters seem to be related with the existence of water-rock interaction with different granitic rocks.

INTRODUCTION

During the last years, several geochemical studies have been carried out on hot (76ºC) and cold (17ºC) $HCO_3/Na/CO_2$-rich mineral waters issuing at the northern part of the Portuguese mainland, associated with fractured Hercynian granitic rocks (fig.1).

The aim of this paper is to review the hydrogeologic investigations performed at Vilarelho da Raia - Pedras Salgadas region using a multi-isotope approach.

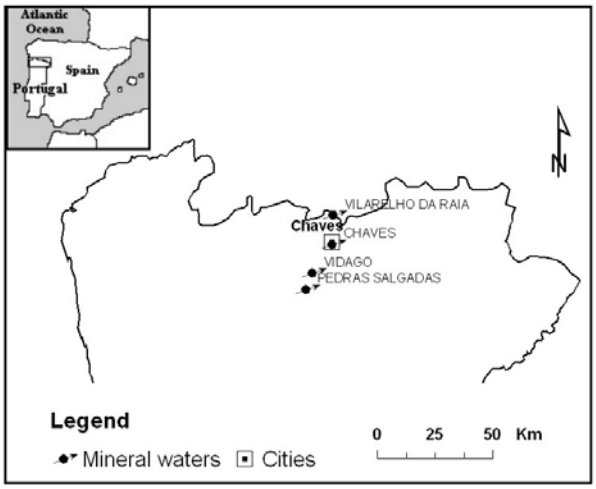

Figure 1. Location of the studied CO_2-rich mineral waters

GEOLOGICAL BACKGROUND

The region under research is located in the tectonic unit of Middle Galicia / Trás-os-Montes sub-zone of the Central-Iberian Zone of the Hesperic Massif. According to several authors (Baptista *et al.* 1993 and Sousa Oliveira and Portugal Ferreira 1996), who described the geology of Vilarelho da Raia - Pedras Salgadas, the main geological formations are: i) Hercynian granites (sin-tectonic - 310 My and post-tectonic - 290 My) and ii) Silurian metasediments of the Upper, Intermediate and Lower Peritransmontano Group, that consists on a sequence of quartzites, phyllites and carbonaceous slates. The most recent formations are Miocene-Pleistocene graben filling sediments with variable thickness, showing their maximum development along the central axis of Chaves Depression.

Tectonically, the region is mainly controlled by the NNE-SSW hydrothermally active fault playing an important role in the circulation of the mineral waters. Marques *et al.* (2000) stated that this structure could play an important role in CO_2 extraction and migration from the mantle to the surface. Sousa Oliveira and Portugal Ferreira (1996) pointed out the fact that the mineral waters emerge in places where the following subvertical fracture systems intersect: 1) N-S to NNE-SSW, 2) ENE-WSW, 3) NNW-SSE to NW-SE, and 4) WNW-ESE to W-E.

GEOCHEMICAL MODEL – QUESTIONS AND ANSWERS

What is the origin of the mineral waters?

$\delta^{18}O$ and δ^2H values of the hot and cold CO_2-rich mineral waters (fig.2) lie on or close to the global meteoric water line (GMWL: $\delta^2H = 8\delta^{18}O + 10$) indicating that they are meteoric waters which have been directly infiltrated into the bedrock. Based on $\delta^{18}O$ and δ^2H values of cold dilute spring water samples collected at different altitudes in the Vilarelho da Raia – Pedras Salgadas region, the local meteoric water line (LMWL: $\delta^2H = 7.01 \pm 0.74$ $\delta^{18}O + 4.95 \pm 3.9$) was calculated (fig. 2). Both hot and cold CO_2-rich mineral waters have δ^2H and $\delta^{18}O$ values similar to those of local meteoric waters, suggesting that there is no water-rock interaction at elevated temperatures.

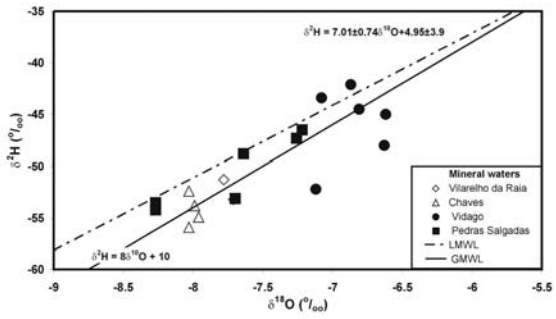

Figure 2. Plot of $\delta^{18}O$ vs δ^2H ($^0/_{00}$ vs V-SMOW) for the CO_2-rich mineral waters

Isotopic composition of meteoric groundwater generally matches the mean composition of precipitation over the recharge area (IAEA, 1981). So, we have used locally derived groundwaters (cold dilute spring waters) to characterise the altitude dependence of the isotopic composition of the CO_2-rich mineral waters. The results obtained indicate that in the studied region there is a decrease in $\delta^{18}O$ of -0.22 $^0/_{00}$ per 100 m rise in elevation, which is similar to the -0.2 $^0/_{00}$ shift per 100 m reported by IAEA (1981) for regions of temperate climate. Based on this values we have achieve an approximate mean recharge elevation for the studied CO_2-rich mineral waters, namely: Chaves and Vilarelho da Raia 1000m a.s.l; Vidago 500 – 700m a.s.l.; Pedras Salgadas 800 – 1200m a.s.l. According to the geomorphology of

the region, the recharge of the studied mineral waters seems to occur preferentially on the E block of the Chaves Depression (Padrela Mountain).

What is the source of CO_2 in the mineral waters?

$\delta^{13}C$ determinations carried out on total dissolved inorganic carbon (TDIC) of the CO_2-rich mineral waters gave values lying in the range of $-6^0/_{00}$ to $-1^0/_{00}$ (Marques *et al*. 2000) indicating a deep-seated (upper mantle) origin for the CO_2. These results corroborate the $\delta^{13}C$ values measured on CO_2 gas samples ($\delta^{13}C(CO_2) = -5.72^0/_{00}$ vs PDB) referred by Almeida (1982), for the case of Chaves thermomineral waters.

Pérez *et al*. (1996) measured and discussed the $^3He/^4He$ and $^4He/^{20}Ne$ from terrestrial fluids in the Iberian Peninsula. According to them, the isotopic signature of helium in a fluid sample from Cabreiroa, located at the same NNE-trending fault of the studied CO_2-rich thermomineral waters, is significantly higher than typical crustal helium ($^3He/^4He$ value of 0.69). Pérez *et al*. (1996) estimated that, in the fluid sample from Cabreiroa, the helium's fractions from mantle, crustal and atmospheric reservoirs were 8.35 %, 91.62 % and 0.02 %, respectively. The relatively high $^3He/^4He$ found in Cabreiroa sample corroborates an important mantle-degassing component.

What is the age of the mineral waters?

The systematic presence of tritium (2 to 4.5 TU) in some of the Vidago and Pedras Salgadas cold CO_2-rich mineral waters is attributed to a less deep flowpaths. In the case of Chaves mineral waters, which are characterised by the absence of ^3H and a ^{14}C activity of 4.3 pmc, the temperature (76ºC) indicates the existence of a geothermal system associated with a relatively deep circulation and consequently a large residence time (Marques *et al*. 2000). Nevertheless, admitting a residence time large enough for all tritium decay, one have to consider an income of carbon, free of ^{14}C, to the water system. This assumption is based on the $\delta^{13}C$ signatures ($-2.8^0/_{00}$ vs PDB) presented by Chaves mineral waters. In contrast, in some of the cold (17ºC) CO_2-rich mineral waters from Vilarelho da Raia - Pedras Salgadas region, the ^3H content is not in agreement with the ^{14}C values (7.9 to 9.9 pmc) found in these mineral water systems (the apparent ^{14}C groundwater ages are close to 9 ka BP). These results indicate that total carbon in the recharge waters is being masked by larger quantities of CO_2 (^{14}C-free) introduced from deep-seated (upper mantle) sources.

What is the main water-rock interaction processes occurring at depth?

Sr isotopes have been used as tracers in water-rock interactions studies (McNutt *et al*. 1990) because the high atomic weight of strontium avoids isotopic fractionation by any natural process. So, the measured differences in the $^{87}Sr/^{86}Sr$ ratios in waters can be ascribed to the mixing of Sr derived from different rock sources with different isotopic compositions.

Differences in the $^{87}Sr/^{86}Sr$ values of the studied mineral waters seem to be related with the existence of water-rock interaction with different granitic rocks.

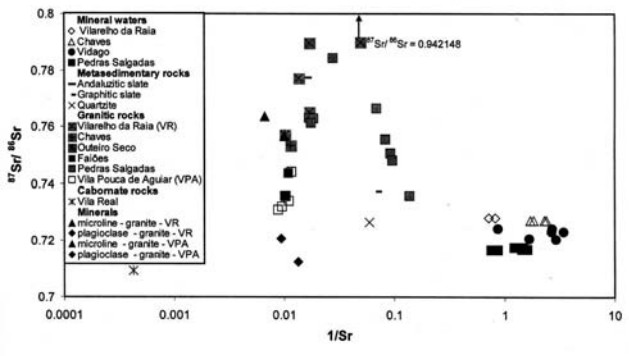

Figure 3. Plot of 1/Sr vs $^{87}Sr/^{86}Sr$ for the rocks, minerals and CO_2-rich mineral waters

A comparison of $^{87}Sr/^{86}Sr$ values among the mineral waters and the rocks/minerals from Vilarelho da Raia – Pedras Salgadas area is shown in fig.3. The Sr isotopic signatures indicate that no equilibrium has been reached between the mineral waters and the whole rocks. On the other hand, the similarity of the $^{87}Sr/^{86}Sr$ values between the mineral waters and the plagioclases from the granitic rocks suggests that the plagioclase dissolution is the main water-rock interaction process.

The hypothesis of the existence of water limestone interaction, to explain the origin of CO_2, should be considered rather limited once the composition of the Sr and the $^{87}Sr/^{86}Sr$ ratio of limenstone is quite different from the mineral waters. This interpretation was also based on the fact that the CO_2-rich mineral waters displaying the less negative $\delta^{13}C$ value (Vidago AC18: $-1.0^0/_{00}$ vs PDB) show a higher $^{87}Sr/^{86}Sr$ ratio. Than, the most plausible explanation for the less negative $\delta^{13}C$ values in some of the thermomineral could be the existence of fractionation at low temperature, during the release of dissolved CO_2.

CONCLUDING REMARKS

CO_2-rich mineral waters from Vilarelho da Raia - Pedras Salgadas region represent locally meteoric waters recharged at different altitudes. Isotopic signatures of C present in these mineral water systems indicate a deep-seated (upper-mantle) origin for the CO_2. CO_2 is, most probably, initially transported as a separate gas phase that is subsequently mixed with the more or less deep circulating meteoric waters, in a fractured aquifer system. Other solutes (such as Na and HCO_3) are originated from the local granitic rocks, being the dissolution favoured by the high CO_2 content of the circulating waters.

ACKNOWLEDGMENTS

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REFERENCES

Almeida FM (1982) Novos dados geotermométricos sobre águas de Chaves e de S. Pedro do Sul. Com Serv Geol Port 68(2):179-190

Baptista J, Coke C, Dias R, Ribeiro A (1993) Tectónica e geomorfologia da região de Pedras Salgadas/Vidago e as nascentes minerais associadas. In: Comunicações da XII Reunião de Geologia do Oeste Peninsular I:125-139

IAEA (International Atomic Energy Agency) (1981): Stable isotopes hydrology. Deuterium and oxygen-18 in water cycle. IAEA, Vienna, Technical Reports Series 210

Marques JM, Carreira PM, Aires-Barros L, Graça RC (2000) Nature and role of CO_2 in some hot and cold HCO_3/Na/CO_2-rich Portuguese mineral waters: a review and reinterpretation. Environ Geol 40(1):53-63

McNutt RH, Frape SK, Jones MG, MacDonald IA (1990) The $^{87}Sr/^{86}Sr$ values of Canadian Shield brines and fracture minerals with applications to groundwater mixing, fracture History, and geochronology. Geochim Cosmochim Acta 54:205-215

Pérez NM, Nakai S, Wakita H, Albert-Bertrán JF, Redondo R (1996) Preliminary results on $^3He/^4He$ isotopic ratios in terrestrial fluids from Iberian peninsula: seismoctectonic and neotectonic implications. Geogaceta 20(4):830-833

Sousa Oliveira A, Portugal Ferreira MR (1996) A estruturação do sistema graben – horst cruzado da região de Pedras Salgadas – Vidago (Norte de Portugal): enquadramento das emergências hidrominerais associadas. Proceedings do 3º Congresso da Água / VII SILUBESA Lisboa, III:123-130

An isotopic approach to sustain recharge sources of low-temperature geothermal waters, North Portugal

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A b s t r a c t : Caldas do Moledo is an important low-temperature (45ºC) geothermal field situated in the northern part of the Portuguese mainland. These bicarbonate-sodium-sulphurous mineral waters (used in local spas) issue from natural springs and drilled wells along the major NNE-SSW Variscan trending fault system of Verin-Régua-Penacova. The results obtained indicate that Caldas do Moledo geothermal waters are meteoric waters infiltrated at high altitude areas (850-1000 m a.s.l.). Considering the isotopic (^{18}O, ^{2}H) signatures and the hydrogeologic and geotectonic evidences, a main recharge area located at NW Caldas do Moledo was identified. The apparent ^{14}C groundwater age (15.66 ± 2.86 ka BP) was estimated in the TDIC using the $\delta^{13}C$ values for correction.

INTRODUCTION AND GEOLOGICAL SETTING

In this work, a review of the results of studies on the origin of Caldas do Moledo geothermal waters, issuing in the N part of Portuguese mainland, is presented. Water samples from the geothermal and shallow groundwater systems were collected, from boreholes and springs, during five field campaigns (1990-1999). The investigations have been carried out to improve the knowledge on the identification of recharge areas, local and/or regional underground flow and mixing processes between deep geothermal waters and local shallow groundwaters.

The Caldas do Moledo spa is located in the region of the famous Port wine vineyards, in the Douro River valley. The geothermal borehole waters, with discharge temperature of 40-46 ºC, are being used in the local spa for diversified treatments. Recently, a low enthalpy geothermal use, for heating purposes, has been considered.

Figure 1. Schematic location of Caldas do Moledo (CM) area

The main morphostructural feature of the Caldas do Moledo area is the Douro valley, which is bounded northward by the Marão mountain ridge (*ca.* 1415m) and southward by the Meadas ridge. The study area is located in the Central Iberian Zone of the Iberian Massif (Ribeiro *et al.* 1990). Previous studies (Cabral 1995, Carvalho 1996, Baptista *et al.* 1998, Espinha Marques *et al.* 2001a) pointed out that the most important tectonic structures in the region are the NNE-SSW Régua-Verin fault lineament (RVFL) and the WNW-ESE to NW-SE Vigo-Régua shear zone (VRSZ) (fig.1).

In the region, the most abundant lithotypes are the metasedimentary rocks of lower Cambrian age. Variscan granitic rocks, including aplite and pegmatite veins, were mapped (Espinha Marques *et al.* 2001a,b).

The occurrence of the geothermal waters seems to be mainly conditioned by the regional fault lineament intersections and the lithotectonic boundary between the metasedimentary rocks and the granitic rocks.

RESULTS AND DISCUSSION: AN OVERVIEW

During the earlier field campaigns only the Nova natural spring and the borehole AC1 were sampled for geochemical and isotopic studies. The results obtained indicated that, at Caldas do Moledo area, the geothermal waters are characterised by the following main features (Marques *et al.* 1999): i) relatively high pH values (between 8.0 and 10.0); ii) dry residuum values usually in the range of 200 to 350 mg/ l; iii) HCO^{3}–Na facies; iv) presence of reduced species of sulphur ($HS^- \cong 2.5$ mg/l); v) high silica values, usually representing more than 15% of total mineralisation; vi) fluoride concentrations around 20 mg/L.

As indicated by the HCO_3–Na facies of the geothermal waters, the reservoir rock should be mainly the granite. The presence of relatively high amounts of fluorine in the geothermal fluids could be the result of water interaction with some particular minerals that can be present either in the granitic or in the pegmatitic rocks of the region.

In the case of Caldas do Moledo AC1 geothermal waters, the results of the several geothermometers indicate different reservoir temperatures. The SiO_2 geothermometers indicate higher temperatures (± 90ºC) than the Na-K-Ca (β=4/3) and K^2/Mg geothermometers (± 70ºC). Concerning geothermal waters from Nova spring, the K^2/Mg geothermometer indicates low reservoir temperatures (± 40ºC). Local shallow spring waters are much more concentrated in Mg (between 0.40 to 10.0 mg/L) than the geothermal waters. So, mixing of deep geothermal waters with local shallow groundwaters could explain the lower K^2/Mg ratios found in Caldas do Moledo geothermal spring Nova and the lower estimated K^2/Mg temperatures. In fact, geothermal waters from Nova spring are characterised by higher Mg concentrations than the geothermal waters from the borehole AC1. Using i) the mean reservoir temperature given by the Na-K-Ca and K^2/Mg geothermometers (AC1 geothermal waters), ii) the local mean annual temperature (15ºC), and considering a mean geothermal gradient value of 30ºC/km, we have estimated the depth reached by the geothermal water system (1.8 km).

Stable isotopes (^{18}O, ^{2}H) were used as natural tracers for problems concerning the origin of waters and the identification of recharge areas and underground flow paths, and the radioactive isotopes (^{3}H, ^{14}C) for questions concerning the dynamics of the groundwater flow system.

The low ^{3}H values (0–1 TU) found in Caldas do Moledo geothermal system (AC1 borehole) indicated a long residence time of the geothermal waters. This hypothesis was later supported by the low ^{14}C content (13.97 ± 1.33 pmc) determined in the total dissolved inorganic carbon (TDIC) of AC1 borehole waters. The apparent ^{14}C groundwater age (15.66 ± 2.86 ka BP) was estimated in the TDIC using the $\delta^{13}C$ values for correction. The $\delta^{13}C$ value obtained $\delta^{13}C_{TDIC}$ = -15.45 ºoo *vs* PDB) indicates that the existence of water-carbonate rock interaction along the flow path should be rather small, since marine carbonates and limestones usually present $\delta^{13}C$ values around 0 ºoo. The presence of ^{3}H in Nova spring geothermal waters (2–7 TU) could be associated with i) a shorter residence time (when compared with AC1 borehole waters) allowing the detection of seasonal variations and/or ii) a mixing process with shallow groundwaters.

The pattern observed requires the shallow groundwaters diluting Caldas do Moledo geothermal spring waters to be i) relatively young, to explain the higher ^{3}H values and ii) derived from local infiltration at low altitude sites, to explain the enrichment in ^{18}O and ^{2}H values. The mixing process should be responsible for the pH decrease observed in the geothermal spring waters, inducing Ca and Mg dissolution. Effectively, the Ca and Mg concentrations are very low in AC1 geothermal borehole waters, whereas these metals are higher in Nova geothermal spring waters. Furthermore, Ca and Mg are very often added to cooled waters by a reaction with the rock, as stated by several authors, particularly with regard to French waters of the Massif Central (e.g., Michard *et al.* 1981, Criaud and Fouillac 1986).

Spring water samples were collected at different altitude sites. The altitude dependence of the isotopic composition of the Caldas do Moledo geothermal waters was therefore determined by $\delta^{18}O$ values associated with these shallow groundwater samples. The isotopic gradient obtained for $\delta^{18}O$ was -0.12 $^{o}/_{oo}$ / 100 m of altitude. The value obtained is according to the isotopic gradients described in IAEA (1981). The isotopic signatures allowed to estimate the mean recharge altitude of Caldas do Moledo geothermal waters (between 850 and 1000 m a.s.l.). Considering the isotopic information and geomorphologic and tectonic evidences, two possible recharge areas were identified in the region. The referred elevations occur to NW and WNW of Caldas do Moledo, suggesting that the NW-SE Vigo–Régua shear zone should play an important role in groundwater recharge and circulation towards the NNE-SSW Régua–Verin fault lineament. This NNE-SSW fault system seems to act as the most likely channel for the geothermal waters ascent.

All samples lie on or close to the Global Meteoric Water Line $\delta^{2}H = 8\ \delta^{18}O + 10$ defined by Craig (1961). These analytical results indicate that all the water samples are meteoric waters that have not been subjected to surface evaporation. It should also be stated that in the geothermal samples no evidence of water-rock interaction at high temperatures was found. In order to estimate the Local Meteoric Water Line, orthogonal regression was the used method, since both oxygen-18 and deuterium in these calculations are independent variables. The Douro river waters were not considered in these calculations due to the possible evaporation processes that might occur in this water system. In this case, the equation of the local meteoric water line is $\delta^{2}H = (7.40 \pm 1.02)\ \delta^{18}O + (8.17 \pm 5.95)$; (n = 24; r = 0.737), and is in good agreement with the values found in Mediterranean regions (IAEA 1981).

Two main distinct groups of waters can be recognised ($\delta^{2}H$ *vs* $\delta^{18}O$ diagram): i) more enrichment in heavy isotopes, represents the precipitation in the region and the groundwaters from the shallow and geothermal systems; ii) more depleted, consists of the Douro river waters. Concerning group i), the total variability of stable isotopic composition of Caldas do Moledo geothermal waters, range between – 42.7 and –35.8 $^{o}/_{oo}$ for $\delta^{2}H$ and from – 7.00 to –6.26 $^{o}/_{oo}$ for $\delta^{18}O$, while within the shallow groundwaters, the isotopic composition varies from –41.4 to – 32.2 $^{o}/_{oo}$ and from –6.53 to –5.64 $^{o}/_{oo}$ for $\delta^{2}H$ and $\delta^{18}O$, respectively. In a first approach, the isotopic data obtained seem to confirm the existence of a mixing mechanism, between the geothermal spring waters (depleted in heavy isotopes) and the waters from the shallow aquifers (enriched in heavy isotopes).

CONCLUDING REMARKS

The isotopic signatures of the geothermal waters, depleted in ^{18}O and ^{2}H relative to local shallow groundwaters, points out to a recharge area located at high elevations (850–1000 m a.s.l.). During the long residence time (apparent ^{14}C groundwater age 15.66 ± 2.86 ka BP) the infiltrated waters are mineralised by water-granite interaction in a low-temperature environment. The NW Vigo–Régua shear zone seems to control the regional circulation of these waters, while the NNE-SSW Régua–Verin fault lineament seems to be responsible for their ascent and discharge. As shown by means of chemical and isotopic data, some of the geothermal spring waters of Caldas do Moledo area (e.g., Nova spring) should be faced as the result of mixing between shallow and geothermal groundwaters.

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REFERENCES

Baptista J, Cabral J, Ribeiro A (1998) Seismotectonics of Chaves and Moledo mineral springs in Penacova-Régua-Verin Fault Zone. Comun Inst Geol Min 84, 1:D69-D72

Cabral J (1995) Neotectónica em Portugal Continental. Mem Inst Geol Min 31:1-265

Carvalho JM (1996) Mineral water exploration and exploitation at the Portuguese Hercynian massif. Environ Geol 27:252-258

Craig H (1961) Isotopic variations in meteoric waters. Science 133:1703-1703

Criaud A, Fouillac C (1986) Étude des eaux thermominérales carbogazeuses du Massif Central Français. II. Comportement de quelques métaux en trace, de l'arsenic, de l'antimoine et du germanium. Geochim Cosmochim Acta 50:1573-1582

Espinha Marques J, Chaminé HI, Carvalho JM, Borges FS (2001a) Tectónica regional do sector de Caldas do Moledo–Granjão–Cidadelhe (Falha de Penacova–Régua–Verín, N de Portugal): implicações no controlo das emergências hidrominerais. Comun Inst Geol Min 88:203-212

Espinha Marques J, Marques JM, Chaminé HI, Graça RC, Carvalho JM, Aires-Barros L, Borges FS (2001b) The newly described 'Poço Quente' thermal spring (Granjão–Caldas do Moledo sector, N Portugal): hydrogeological and tectonic implications. Geociências 15:19-35

IAEA – International Atomic Energy Agency (1981) Stable isotope hydrology. Deuterium and oxygen-18 in the water cycle. Technical Reports Serie,s 210

Marques JM, Aires-Barros L, Graça RC (1999) Isotopic and chemical signatures of low-temperature sulphurous mineral waters (Northern Portugal): preliminary results. Geoth Res Counc Transact 23:327-332

Michard G, Fouillac C, Grimaud D, Denis J (1981) Une méthode globale d'estimation des températures des réservoirs alimentant les sources thermales. Exemple du Massif Central Français. Geochim Cosmochim Acta 45:1199-1207

Ribeiro A, Quesada C, Dallmeyer RD (1990) Geodynamic evolution of the Iberian Massif. In: Dallmeyer RD, Martínez-García E (eds.) Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, 397-410

Origin of salts in a fractured bedrock aquifer in the Central West Region, NSW, Australia

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A b s t r a c t : The origin of salts contained within fractured bedrock aquifers was determined using hydrogeochemical techniques, that differentiated marine and terrestrial sourced aquifers, within the geologically complex Spicers Creek catchment. Identification of the salt source in this catchment is an important factor for the implementation of land management options to halt and/or reverse land degradation processes. Groundwaters from the Palaeozoic basement rocks contain different geochemical signatures. The Oakdale Formation groundwaters contain lower Sr^{87}/Sr^{86} ratios and high concentrations of Sr, B, Na, Cl and As indicating that salts are derived from sediments that were deposited within a marine environment. The Gleneski Formation groundwaters contain higher Sr^{87}/Sr^{86} ratios indicating a terrestrial sourced lithology. The $^{87/86}Sr$ isotope was used to obtain the boundary between marine and terrestrial salt origin and $\delta^{18}O$ and δD isotopes were used to identify the origin of water. Groundwater chemistry and isotopes have allowed differentiation of various Palaeozoic lithologies within the catchment and enabled interpretation of the flow conditions within these highly fractured environments.

INTRODUCTION

Groundwaters contained within fractured bedrock aquifers located in the Spicers Creek catchment contain varying salt contents and unique groundwater chemistries, depending on the aquifer lithology and depositional history of the sediments. There are three main aquifers within the catchment; they include the Palaeozoic Oakdale and Gleneski Formations and Mesozoic sandstones and siltstones. The origin of salts contained within these fractured bedrock aquifers will be determined using hydrogeochemical techniques, which will allow for the differentiation of aquifers within this geologically complex catchment. Spicers Creek catchment is located approximately 400 km west of Sydney, in the Central West region of New South Wales, Australia. Soils are fertile and support a healthy dryland agricultural industry of wheat and canola products. The Spicers Creek catchment is an example of a catchment experiencing fluctuating water tables, waterlogging and salinisation of surface water leading to a decline in agricultural productivity. Identification of the source of salt in this catchment is an important factor for the implementation of land management options to halt and/or reverse land degradation processes.

HYDROGEOLOGY

The geology of the Spicers Creek catchment is very complex; it is situated on the southern margin of the sedimentary Gunnedah and Surat Basins, which overlie the western margin of the Lachlan Fold Belt in New South Wales, Australia. The Lachlan Fold Belt has been regionally metamorphosed and contains extended north-south trending faults, folds and fractures, which influence groundwater flow patterns in these aquifers. The Palaeozoic metavolcanics range in age from Ordovician to Devonian age and were deposited in sub-marine to marine environments. The Ordovician Oakdale Formation consists of volcanics and volcaniclastic sediments that were deposited in a deep marine environment. The Silurian Gleneski Formation consists of volcaniclastic sandstones and volcanics and was deposited in a terrestrial environment close to a marine transgression sequence. The overlying Mesozoic sediments of the Gunnedah and Surat Basins consist of sandstones and siltstones that range in thickness from 0 to 80 m throughout the catchment. A thin veneer of unconsolidated colluvial/alluvial material ranging in thickness from 0 to 15 m covers the study area. Groundwater flow in the fractured bedrock aquifer follows a northwestly direction and artesian flow is encountered in several parts of the catchment.

GROUNDWATER CHEMISTRY

Groundwater chemistry in the Spicers Creek catchment is varied and will be discussed according to the aquifer type and location within the aquifer where it has been sampled. The Oakdale Fr. contains groundwaters that range from Na-Mg-Ca-HCO_3-rich waters to Mg-Na-Cl and Na-Cl-rich waters. Groundwater salinity ranges from 4070 µS/cm to 14510 µS/cm. The variability in salinity in this unit is primarily due to the depth that the groundwaters were sampled. Samples obtained from 30 to 50 m b.g.l., contain salinities ranging from 4070 to 6320 µS/cm, the deeper sections of the aquifer ~110 m has a higher salinity, over 14500 µS/cm. Saline groundwaters are encountered in the lower sections of the Oakdale Fr. and the shallow more weathered zone of the aquifer has been leached of salts. The Gleneski Fr. contains fresher groundwaters that range from Mg-Na-Cl-HCO_3-rich waters to Na-HCO_3-Cl-rich waters. Salinities range from fresh 954 µS/cm to brackish 6645 µS/cm. Groundwaters located in the upper section of this aquifer contain brackish waters with fresh waters in the deeper sections. Groundwaters from the Mesozoic units range from Na-HCO_sCl-rich and Mg-Na-Cl-rich to Na-Cl-rich. Salinities range from 3065 to 21,250 µS/cm. The highest salinity was encountered in the lower sections of the Mesozoic aquifer, where this unit overlies the Oakdale Fr. Groundwater salinity in the Spicers Creek catchment is related to water-sediment interaction and mixing of groundwaters between Palaeozoic and Mesozoic aquifers.

ORIGIN OF SALINITY IN THE FRACTURED AQUIFERS

Groundwater within the Palaeozoic basement aquifers of the Spicers Creek catchment are brackish to saline with most waters plotting along a 1:1 line on a Na versus Cl graph, indicating NaCl is leaching from sediments and is the main contribution of salts to groundwaters. Groundwater samples plotted on Fig.1a with ^{18}O versus D follow the general trend line for seawater with an enrichment of ^{18}O and D relative to other samples in the catchment. This indicates that the Oakdale Fr. groundwaters are experiencing an increase in salinity due to the dissolution of connate salts contained within marine sediments. Groundwater samples from the Gleneski Fr. plot along the LMWL ($\delta D^0/_{00} = 9.74\delta^{18}O + 16.63$). Mesozoic groundwaters contain isotopic signatures similar to the Oakdale Fr. and the Gleneski Fr. groundwaters depending on the location in the catchment, indicating that mixing is occurring between the Mesozoic and underlying Palaeozoic aquifers groundwaters.

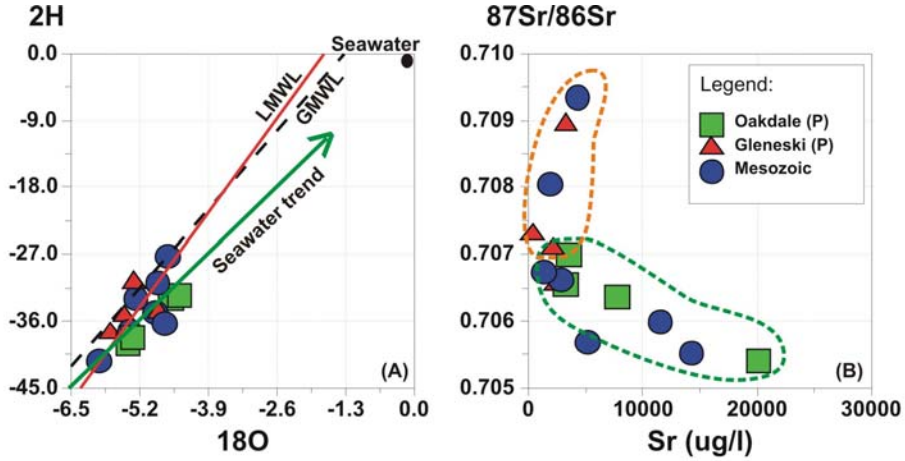

Figure 1.(a) Deuterium versus 18O, (b) 87Sr/86Sr versus Sr2+, for groundwaters in Spicers Creek catchment

Aquifer	EC uS/cm	Na mg/L	Cl mg/L	Sr ug/L	B ug/L	As ug/L	$^{87}Sr/^{86}Sr$	^{18}O	^{2}H
Oakdale F. saline	14510	2650	4718	20100	260	12.8	0.705407	-4.45	-32.5
Oakdale F. brackish	4460	618	1059	3220	291	19.4	0.706555	-5.43	-38.9
Gleneski F. saline	6645	741	1973	3250	240	5.79	0.708938	-4.84	-34.8
Gleneski F. fresh	954	167	160	344	118	1.08	0.707292	-5.31	-30.8
Mesozoic F. lower	21250	4530	6977	11500	172	26.5	0.706003	-4.74	-36.2
Mesozoic F. upper	3415	491	799	188	245	0	0.70806	-4.92	-34.7

Table 1. End-member groundwaters for the different aquifers in Spicers Creek catchment

Sr^{87}/Sr^{86} ratios range from 0.709396 to 0.705407 indicating that these groundwaters fall within the range of seawater ~0.706 to ~0.709. The Oakdale Fr. waters are less radiogenic than the Gleneski Fr. waters as indicated in Fig.1b Two general trends can be observed from this isotopic data due to the different aquifer lithologies. The Oakdale Fr. groundwaters contain lower Sr^{87}/Sr^{86} ratios indicating that Sr is derived from sediments that were deposited within a marine environment. The Gleneski Fr. groundwaters are slightly more enriched in Sr^{87}, which indicates that these groundwaters were derived from sediments that are K-feldspar rich or clay rich due to the lower total Sr concentrations and higher ^{87}Sr than the Oakdale Fr.

TRACE ELEMENTS

Trace elements were determined to aid in the differentiation of aquifer lithology and determine mixing between the underling fractured Palaeozoic aquifers with the overlying Mesozoic aquifers. Trace elements such as Sr, B, As, Cr, Zn, Cu and Ni were detected at elevated concentrations within this natural groundwaters system. The presence of elevated Sr, B and As in the Oakdale Fr. gives further evidence that these groundwaters are derived from marine sourced lithologies and hence the salts are of marine origin in this unit. The Oakdale Fr. contains high Sr values ranging from 3,200 to 20,100 µg/L, high As ranging from 5 to 19 µg/L and high B levels ranging from 229 to 291 µg/L. The Gleneski Fr. groundwaters are high in trace elements such as Cu, Cr, U and Ga. The trace elements present in these groundwaters do not suggest a marine origin for this unit, indicating a terrestrial environment of deposition. The Mesozoic sediments contain waters of the greatest salinities and hence the greatest amount of trace elements. As ranges from 5 to 27 µg/L and Ag 1 to 5 µg/L. They also contain elevated Ni, Co, Sc and V levels. Sr and B concentrations are less than those of the Oakdale Fr. but are quite high in the lower Mesozoic groundwaters that are experiencing upward leakage of the Oakdale Fr. waters. Groundwaters from the Mesozoic aquifers contain varied chemistry due to mixing of waters from the various rock types. Groundwater samples obtained from the lower part of the Mesozoic aquifer that overly Oakdale Fr. contain similar geochemical signatures to that of the Oakdale Fr. waters. Groundwaters from the Mesozoic aquifer that overly the Gleneski Fr. are fresher and retain terrestrial sourced trace element signatures.

CONCLUSION

Groundwaters in the Spicers Creek catchment contain unique groundwater chemistry depending on the fractured rock aquifer it evolves from and mixing processes within fault and fracture zones within these units. The Oakdale Fr. contains connate salts trapped within the aquifer material that were deposited in a marine environment. Trace elements and isotopes further indicate that salts present within these groundwaters are derived from marine environments. In some parts of the catchment where the Mesozoic aquifer overlies the Oakdale Fr. leakage between these units is occurring causing salinisation. Groundwaters from the terrestrial sourced Gleneski Fr. are fresher. Mixing of these groundwaters with the overlying Mesozoic aquifer does not pose a threat of salinisation. Using hydrogeochemical and isotopic techniques the source of salt and the environment of deposition of these salts were delineated. The potential for salinisation risk due to the mixing of the Oakdale Fr. waters with the overlying Mesozoic aquifers can be realised and further mapping and structural analysis of this geological unit must be assessed. Delineation of the extent and contact between the overlying Mesozoic aquifers will led to better management practises in the Spicers Creek catchment.

The hydrochemical characteristics of basement aquifer systems in Namaqualand, South Africa

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A b s t r a c t : The groundwater resources for the Namaqualand region are developed predominantly in the basement rocks. The infiltration and flow of water is controlled by the prevailing complex fracture network and can vary in space and time. Such conditions relate to structurally controlled flow systems and varying water chemistry amongst closely spaced fracture systems. It is possible to spatially distinguish between dilute, shallow circulating and relatively young groundwater systems compared to more brackish, slower circulating and relatively older systems. The relatively dilute end-member is associated with dynamic, actively recharged groundwater systems with rapid through-flow rates occurring in the higher lying mountainous regions, or with infiltration through highly transmissive fracture zones within the lower lying valley systems. The more brackish end-member, associated with the valley systems or the lower lying regions, is characterized by a localized, predominantly vertical flow component and possibly a lateral flow component that may approximate an intermediate flow system.

THE STUDY AREA

The study area, situated between latitude 17° 00' - 18°30' and longitude 29°00'- 30°30', is classified by three physiographic regions according to topography, altitude and landforms (fig.1). These regions are the higher lying Bushmanland Plateau to the east, the Namaqualand highlands (which is the escarpment zone), and the lower lying coastal area to the west (Visser 1989).

The study area falls in the arid, hot (BWh), tropical desert climatic region of South Africa, according to the Koeppen classification. The climate of the study area is determined by altitude, topography, and distance from the sea (Midgley *et al.* 1994). The region can be classified as arid to semi-arid, with mountainous regions having higher rainfall than the arid lowland due to orographic effects. Rainfall occurs mostly during the winter months while snow in the highest mountainous regions is not uncommon during the summer months. Potential evapotranspiration can be as much as from 12 to 15 times the precipitation. This high evaporation to precipitation ratio means that salts will easily form on the surface, as well as in the subsurface (Campbell *et al.* 1992 and Van der Sommen and Geirnaert 1990).

GROUNDWATER CHEMISTRY

The groundwater for Namaqualand is generally very similar in character with a dominant NaCl signature throughout the recorded EC ranges and can be described as end-point waters.

The groundwater is generally over-saturated with regard to quartz and under-saturated with respect to amorphous silica (Langmuir 1997; Appelo and Postma 1996; Freeze and Cherry 1979). As a result, quartz and amorphous silica do not exert an important influence on the level of silica in groundwater. The level of dissolved silica, as silicic acid ($H_4SiO_4^0$), for the groundwater of Namaqualand is controlled by the weathering of aluminosilicate minerals with a high silica content indicating the active degradation of silicate minerals.

The groundwater tends to react with both the primary mineral phases and the reactive weathering products or at least with an intermediate, meta-stable phase (i.e. amorphous aluminum oxide and hydroxide phases). The slow reaction kinetics of silicate minerals (including clay minerals) can result in uncertainties about the stability of the weathering products. Molar ratios indicate, however, that the incongruent weathering processes of various aluminosilicate minerals cannot alone account for the groundwater compositions.

PROCESSES INFLUENCING THE GROUNDWATER CHEMISTRY

The dominant NaCl character of the subterranean waters is a result of either the direct infiltration of NaCl dominated precipitation and the preferential dissolution and leaching of the more soluble evaporitic salts during the infiltration process. The groundwater remains NaCl type water throughout the recorded EC ranges.

Active weathering processes, with regard to various mineral phases, are evident throughout the EC range for the lower salinity groundwater. The dilute and relatively aggressive groundwater, associated with higher lying regions, controls the weathering of the mineral phases, while the significant head differences (related to differences in elevation for these mountainous areas) result in dynamic flow systems in which equilibrium is difficult to attain. Weathering products are also continuously removed in such systems and it may thus be inappropriate to apply a thermodynamic approach to characterize the waters in such systems.

A reduction in the weathering capacity, with regard to especially the aluminosilicate and probably the carbonate minerals, is suggested for the relatively deeper, higher salinity groundwater in the lower lying regions of Namaqualand. The reduction in the weathering capacity of the higher salinity groundwater can be related to the infiltration of evaporated waters or the leaching of evaporated salts, the increasing concentrations of dissolved constituents with residence time (i.e. the degree of saturation of the groundwater with various mineral phases), the incongruency relations of various minerals (including carbonates and aluminosilicate minerals), a reduction in the $CO^2_{(aq)}$ (in closed systems), the effects of cation exchange, the common-ion effect or even to the coating of primary minerals by residual clay minerals. The lower lying regions of Namaqualand are characterized by intermittent, periodic recharge events, lower hydraulic gradients within the valley systems and varying hydraulic conductivity values within the saprock to saprolite aquifer zone.

CONCLUSION

The groundwater chemistry is dependant on the point of sampling in either a dynamic or an evaporative and sluggish groundwater system. Stacked, multiple flow systems dominate that differ in terms of the factors influencing both the groundwater flow and chemistry, including the recharge rate, hydraulic gradient and hydraulic conductivity (Acworth 1987). The rate of groundwater

flow influences the reaction rates with primary and secondary mineral phases which in turn influence the resultant groundwater chemistry. Superimposing and probably masking the latter process is the direct infiltration of NaCl dominated precipitation and the preferential dissolution and leaching of the more soluble evaporitic salts during the infiltration process.

Equilibrium conditions are difficult to maintain for open system dissolution of particularly carbonate minerals due to a continuous replacement of CO_2. Open system dissolution conditions probably characterize dynamic groundwater flow systems associated with high hydraulic gradients in the mountainous regions of Namaqualand. These regions are characterized by relatively higher rainfall values, while stable isotopic studies indicate the likelihood of direct rainfall recharge.

The relative distribution of the carbonate (CO_2) species for groundwater in Namaqualand, as a function of pH, represents close-system dissolution of carbonate minerals. Equilibrium conditions are real for closed system dissolution conditions. Such systems, that are closed to $CO_{2(g)}$, may characterize more sluggish groundwater flow systems associated with valleys in the lower lying areas of Namaqualand. Most boreholes in Namaqualand are located in these major fault-controlled valleys with relatively lower hydraulic gradients assumed over the depth of water samples collected.

REFERENCES

Acworth R (1987) The development of crystalline basement aquifers in a tropical environment. Quarterly Journal of Engineering Geology, London 20:265-272

Appelo CAJ, Postma D 1996 Geochemistry, groundwater and pollution. Balkema, Rotterdam, 536pp

Campbell E, Parker-Nance T, Bate G (1992) A Compilation of the information on the magnitude, nature and importance of coastal aquifers in Southern Africa. WRC Report No 370/1/92

Freeze R, Cherry JA (1979) Groundwater. Prentice-Hall Inc, New Jersey

Langmuir D (1997) Aqueous environmental geochemistry. Prentice Hall, New Jersey

Locsey K, Cox M (2000) Chemical character of groundwater in a basalt aquifer, North Queensland, Australia. In: Sililo *et al*. (eds) Groundwater – Past achievements and future challenges. A A Balkema:555–560

Midgeley D, Pitman W and Middleton B (1994) Surface Water Resources of South Africa. Water Research Commission Report 298/1/94

Van der Sommen J, Geirnaert W (1988) On the continuity of aquifer systems on the crystalline basement of Burkina Faso. In: Simmers I (ed) Estimation of Natural Groundwater Recharge. D Reidel Publishing Company:29-45

Visser D (ed) (1989) Explanation of the 1:1.000.000 geological map, fourth edition (1984) Dept Of Mineral and Energy Affairs, Government Printer. ISBN 0-621-12516-4

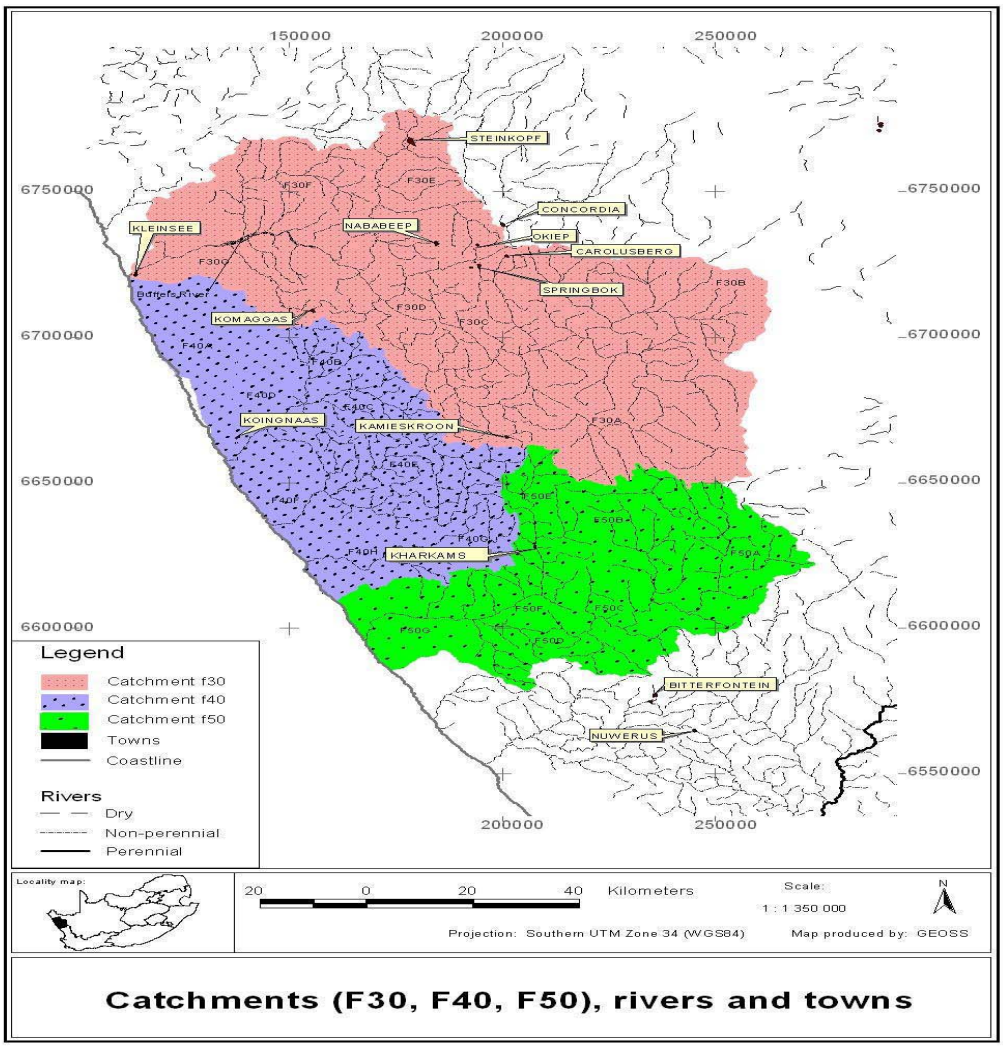

Figure 1. The study area comprising of secondary drainage catchments F30, F40 and F50

The thermal aquifer and the springs of the Serra de Caldas area – Goias, Brazil

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LOCALIZATION AND CLIMATE

The Serra the Caldas is situated is Goias State in the Center of Brazil – 17°46´S 48°40´W. The city of Caldas Novas east and the village of Rio Quente west of the Serra are the places where the hot water is exploited. The Locality of one of the biggest thermal springs in the world, Pousada do Rio Quente, is 350 km south of Brasilia the capital of the country and about 800 km north-north-west of São Paulo. The morphology exposes a remarkable dome (fig.1) with a North-South extension of 14,5 km and East-West extension of 9,4 km. The difference in the altitude is approximately 250 m between the dome and low land.

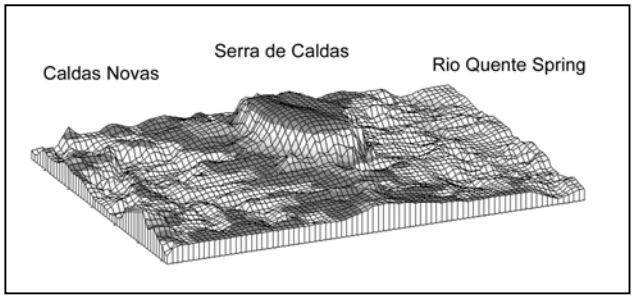


Figure 1. Morphology of the area of the Serra de Caldas

The climate in the region is subtropical. Heavy tropical rainfall up to 2000 mm/y (1500 mm/y mean precipitation) dominates the summer and hard droughts with humidity down to 15% are registered during the winter. The average temperature is 23°C. Due to the summer rain the real evapotranspiration is up to 850 mm/y (Pietzner 2001).

GEOLOGY

Series of middle to young Protorozoic rocks form the area of the Serra de Caldas. The overthrusting of old sediments left a window (Drake 1980) where the younger sediments build up a dome structure of the Serra. Or the younger sediments are overthrusting older sediments (Campos 2000). The last interpretation makes more sense if groundwater quality is respected. The general situation of the ancient stress field is shown in fig.3.

However, the dome consists of pure quartzite with horizontal strata which belong to the Paranoa group. The dip is of low angle striking centroclinal. The overthrusting sediments are an intercalating sequence of schist and quartzite. Thick marlstone banks often are the top layer of the so called Araxa group. The top of the Serra consists of Tertiary Ferroletarite soils.

TECTONIC FEATURES

As shown in fig.2 the quartzite dome of the Paranoa group is surrounded by the Araxa group schist. Many tectonic features can be observed in the satellite image. One part of them can be mapped in the field while others can be constructed by correlation of the well logs. Almost 250 well logs are available and they show a vertical to 80° W dipping of the faults. During the overthrusting phase the quartzite was compressed and formed the same type of morphology in the basement. Gravity measurements show depression in the basement of more than 1000 m below sea level. The faults are passing through the whole section and video logs show an opening of the fractures in depth.

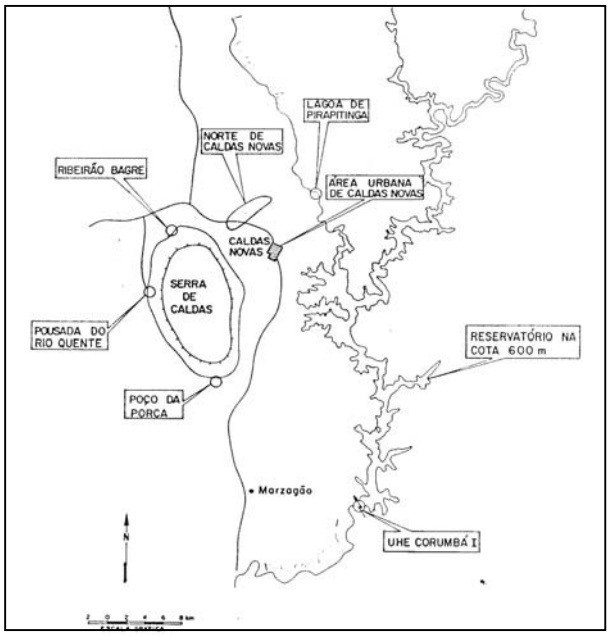


Figure 2. Localization and simplified geology. Serra de Caldas – Paranoá group surrounded by Araxa group

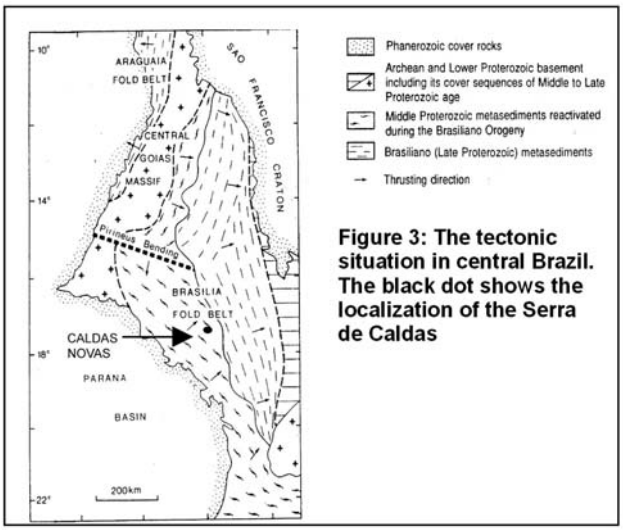

ARAGUAIA FOLD BELT
CENTRAL GOIAS MASSIF
SÃO FRANCISCO CRATON
BRASILIA FOLD BELT
CALDAS NOVAS
PARANA BASIN
200km
Phanerozoic cover rocks
Archean and Lower Proterozoic basement including its cover sequences of Middle to Late Proterozoic age
Middle Proterozoic metasediments reactivated during the Brasiliano Orogeny
Brasiliano (Late Proterozoic) metasediments
Thrusting direction

Figure 3: The tectonic situation in central Brazil. The black dot shows the localization of the Serra de Caldas

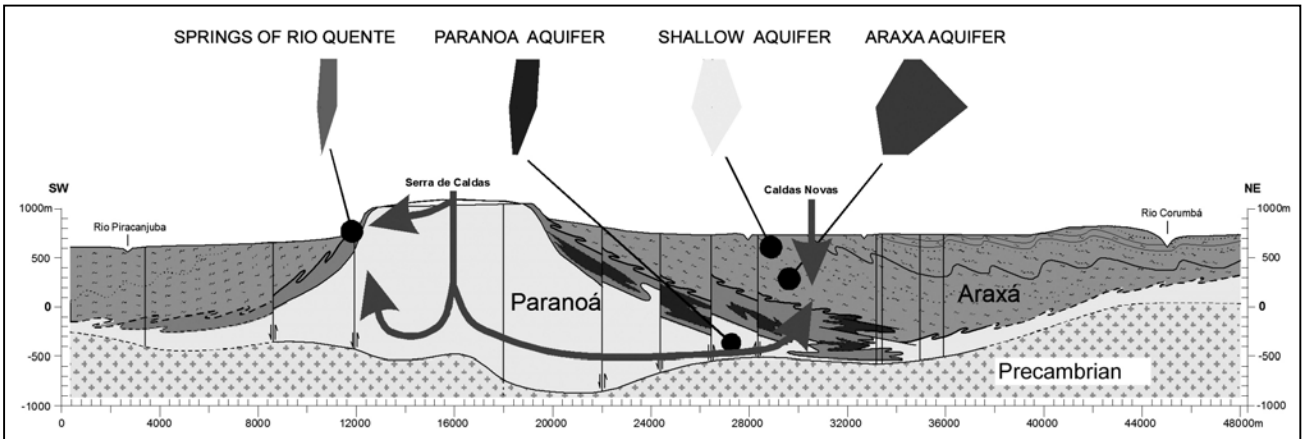
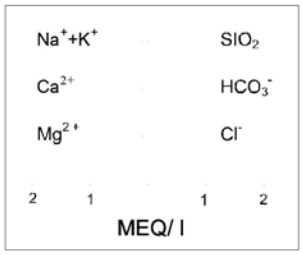


Figure 5: Cross section of the Serra de Caldas showing the vertical faults and the Stiff diagram of the aquifers. The mineralization of springs of and the groundwater of Paronoá aquifer is much lower than the other aquifers The flow of the groundwater demonstrates that the water from the wells is a mixture of little mineralized groundwater from high depth and from the recharge from the Araxa aquifer.



It is important to note that between the Araxa and the Paranoa group the overthrusting left a strong mylonitization (fig.5). The situation is easy to understand from local simplified geological map which shows the localization of the area, too (fig.2).

HYDRAULIC SITUATION

Before 1975 the hot water occurred in three places: Lagoa de Pirapitinga, along the Riberão de Caldas (Caldas River), and the Pousado do Rio Quente. At the last spot the springs have had a flow over 1,66 m^3/s. The other springs have had a flow of approximately of 0,1 m^3/s. Since the number of wells increased the springs along the Caldas River stopped flowing.

The groundwater flow can be explained if the special tectonic of the area is respected. Due to the overthrusting the monolithic structure was deeply effected. The vertical permeability is much higher than the horizontal permeability. Video logs show wide opened vertical fractures in the depth and no horizontal or low angle dipping structures.The recharge of the thermal water takes place on top of the Serra de Caldas. The pressure head in the Serra aquifer was measured 900 m MSL. The springs of the Rio Quente occur in 700 m MSL. The springs yield more water than the calculated and measured recharge of the Serra de Caldas (Pietzner 2001). This result does not match at the first glance with the groundwater analysis. There must be a recharge in other places where only the Paranoa group crops out. This region must be much higher or at least the water table must be as high as in the Serra de Caldas.

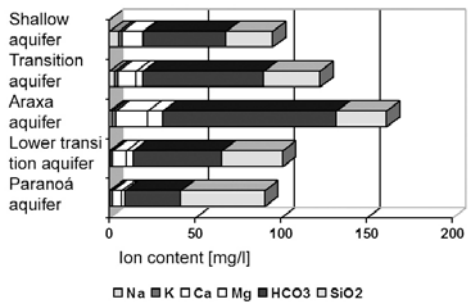


Figure 4. Ion content of the different aquifers

GROUNDWATER CHEMISTRY

The chemistry of the water does not change during the downflow in the dome structure. The spring water gains in SiO_2 but not very much in the other ion content (fig.4). The upwelling water in the fractures shows the same chemistry for the Rio Quente springs and the Paranoá group aquifer.

The top of the Paranoá group consists in large parts of marbles. Therefore the upward flowing groundwater is more dominated from HCO_3^- and Ca^{2+} ions. The groundwater that is recharged in place has a lower content of these ions and is poor in SiO_2. The total ion concentration in the shallow cold water aquifer is higher than in the Paranoá aquifer.

CONCLUSIONS

The chemistry of the water indicates that the flow from the recharge area of the top of the Serra de Caldas is vertical reaching a depth of over 2000 m as the water temperature indicates. The high silica content can be explained as dissolution in depth. The main horizontal flow is possible in this depth and then the water rises up in the faults forming the thermal water springs. The scheme is shown in fig.5. The recharge in the Araxa aquifer does not reach big depth and admixtures with the rising thermal water from the Paranoá aquifer. It is still not clear where the recharge of the quartzite aquifer takes place as the recharge on the top of the plateau is not sufficient for the yield of the springs.

REFERENCES

Albuquerque C (1998) Caldas Novas: Ecológia. Kelps, Caldas Novas /Goiás

CPRM, SMET, Metano, UnB (1999) Geologia e Recursos Minerais do Estado de Goiás e Distrito Federal. Texto Explicativo dos Mapas Geológico e de Recursos Minerais, Escala 1:500.000, Ministério de Minas e Energia - CPRM, Goiânia

Pietner O (2001) Grundwasserneubildung und Grundwasserabfluss im Porenwasserleiter der Serra de Caldas, Goiás, Brasilien. Unplubished dissertation, Technische Universität Berlin

UHE CORUMBÀ (1999) Reservatório e Termalismo , Etapa IV, Regiao de Caldas Novas e Área de Influência de Reservatório, Monitoramento, Vol T.021.98-RO, Rio de Janeiro

Upper Permian brine formation in the Czech part of the Bohemian Massif: paleohydrogeologic environment, hydraulic parameters estimation

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INTRODUCTION

Bohemian Massif Late Palaeozoic sedimentary basins and its crystalline bedrock host a considerable amount of highly mineralised water solutions with ionic composition characterized by apparent sodium, sulphate and chloride ions share. Several genetic hypotheses - from endogenous via in-situ to exogenous and their combinations – are considered when explaining the brines origin. Recent developments in paleogeographic studies as well as recent saline systems investigations connected with effective numerical techniques enable an investigation of exogenous (gravity forced seep) brines origin by means of numerical modeling.

BOHEMIAN MASSIF LATE PALEOZOIC BASINS EVOLUTION

Bohemian Massif consists of several segments cratonized by Hercynian orogeny (Chlupáč and Štorch 1992). Post-orogenic (Middle Namurian to Triassic) strain relief accompanied by gravitational base leveling induced numerous taphrogenic structures development and activated also horizontal fault lines (Pešek *et al.* 1999). Newly developed intra-continental basins entrapped clastic material creating hundreds (thousands) of meters of sedimentary record. During this Carboniferous period predominantly gray colored clastic sequences with coal bearing seams were deposited (Pešek *et al.* 2001)

Ongoing aridization of Central Pangea climate enhanced by the Bohemian Massif intra-continental settings (relative to contemporary climate pattern) triggered arid climatic conditions (Fig.1) that caused intensive predominantly mechanical erosion acting. Continuous subsidence of the basins bottom formed hydrologically enclosed basins with an inner-discharge drainage pattern of sabkhas and playa lakes. In the Permian period, deposition of red beds prevailed (Pešek and Skoček 1998).

SEDIMENTARY RECORD INTERPRETATION – BRINE FORMATION PERIOD

Paleogeographic interpretations (Pešek *et al.* 1999, 2001; Chlupáč 2002; Bouška and Pešek 1981; Blecha, Martínek *et al.* 1997; Kozdrój, Krentz, Opletal 2001 and others) enable us to delimitate more closely (unfortunately mainly due to lack of paleonthological record or any other dating with an error of million(s) of years) periods of brine formation and possible downward seep of brines. There is no doubt about brine generation during Chotěvice and Bohuslavice Formation accumulation. We can hesitate whether Trutnov Formation in its whole extent as well as hiatuses prior to- and after its deposition could be involved into a brine formation period. We can only speculate, what portion of the overall period can be treated this way. Therefore we will define "minimum" to "maximum" interval of highly probable brine formation. The minimum period consists of two minor intervals: Upper Asselian to Lower Sakmarian sedimentation of Chotěvice member – ca 293-288 Ma before present, and Thuringian deposition of Bohuslavice Formation – ca 257-252 Ma b. p. On the other hand the maximum period encompasses the whole interval – ca 293-252 Ma b. p. (estimated using Menning (1995) and Shneider and Roscher (2000) timetables).

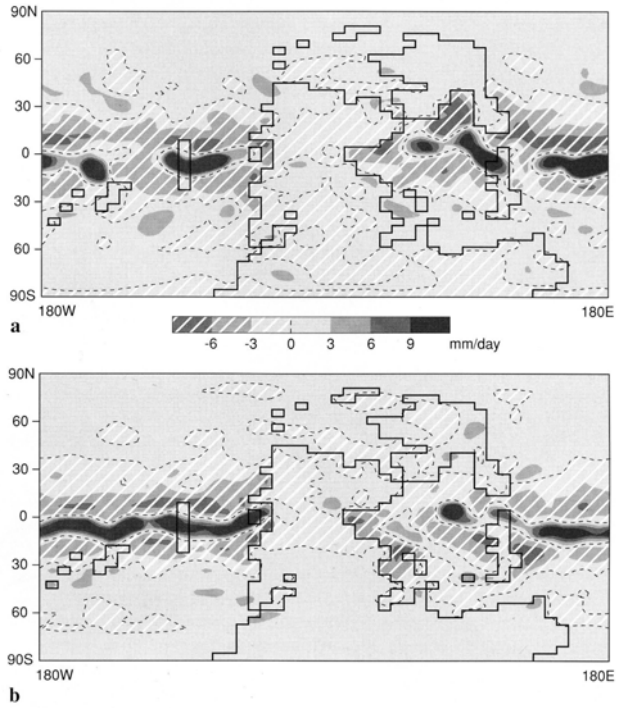

Figure 1. Precipitation minus evaporation for the Late Permian rendered by GENESIS model; a – December, January, February, b – June, July, August (adapted from Barron and Fawcett 1995)

HYDRAULIC PARAMETERS ESTIMATION

Permeability

This crucial hydrogeological parameter is fairly hard to define especially when considering such an extreme time and space dimensions. In case of siliciclastic (predominantly non-carbonate) horizontally layered sedimentary basins fill we can distinguish essentially three geologic features that can affect hydraulic permeability values when we consider greater aerial extent scales. These are gradual facial changes (e.g. coarsening of sediments towards basin margins), fault lines or tectonic zones (both permeable or not) and presence of volcanic bodies (usually acting as aquitards) (Ingebritsen and Sanford 1997). This has to be taken into account when choosing a specific area of possible further investigation via numerical modeling.

Due to all above-mentioned geological features, hydraulic permeability exhibits also apparent anisotropy. Drill-core (vertical) permeability data acquired by Mareš (1967) are ranging from $3x10^{-16}$ to $5x10^{-13}$ m^2 in comparison to field pumping tests result (horizontal component) from Jetel (1969) that lie within $5x10^{-16}$ to $3x10^{-13}$ m^2 interval. In case that we suppose similar vertical and horizontal permeability data statistical distribution, we can interpret the similar data scatter as an isotropic behavior of hydraulic permeability in Permo-Carboniferous sediments. This could be caused for example by a distinct share of fracture-type porosity.

Depth dependence of permeability in Permo-Carboniferous of Central Bohemia was thoroughly studied by Jetel (1969). The most general regression equation derived from wellborn tests results presented by the author is

$$\log K = -12{,}48 - 0.00380\ H, \qquad [1]$$

where K [m^2] is hydraulic permeability and H [m] stays for depth. Value of K obtained for H = 0 (at today's geographic surface), however, characterizes material that has undergone certain compaction due mainly to lithostatic pressure caused by overlying Permian or Cretaceous sediments that have been eroded during ongoing geological times. Here we are about to make a particular simplification by assuming the equation [1] valid even for values of H<0. This is supported by Pešek and Skoček (1999) who considered fairly rapid diagenetic lithification of Permian alluvial sediments – especially under the arid climate.

Then, knowing the maximal overburden thickness we can expand the equation [1] to the "actual Permian" surface and determine the permeability values anywhere below the surface. The total thickness of overlying formations denuded was estimated by Jetel (1969). He compared clays porosity values determined on drill-core samples with other empirical porosity depth-dependence curves. His estimation ranged between 1400 and 2300 m going from Kladno-Rakovník Basin via Mšeno-Roudnice Basin further northeastward. On the other hand, Mareš (1968), who studied rock densities over the sequence, received values from 600 m (for Kačice region) to 750 m (at Slaný area). Simple logarithmic appraisal of porosity values fails (overestimates) for smaller depths close to the surface (Mareš 1968) because of not-yet undergone compaction or already experienced weathering. Permeability estimations fail in the same way, most probably because of a close relation between both properties. Guess of permeability by course of Jetel (1969) offers following 100 m depth permeability values for every single actual surface elevation mentioned above (Tab.1). Regardless the data accuracy this comparison only suggests to use about 1000 m denuded overburden thickness for any numerical methods applied to this problem using the data from Jetel (1969).

Hydraulic parameters	Thickness of denuded sedimentary column (m)			
	600	750	1400	2300
K_{min} (m^2)	1.4×10^{-12}	3.8×10^{-12}	3.4×10^{-10}	1.7×10^{-7}
K_{avg} (m^2)	2.6×10^{-11}	9.8×10^{-11}	2.9×10^{-8}	7.6×10^{-5}
K_{max} (m^2)	4.7×10^{-10}	2.3×10^{-9}	2.3×10^{-6}	3.3×10^{-2}
k_{min} m/s)	1.4×10^{-5}	3.8×10^{-5}	3.4×10^{-3}	1.7
k_{max} m/s)	4.7×10^{-3}	2.3×10^{-2}	2.3×10^{1}	3.3×10^{5}

Table 1. Estimated hydraulic parameters in 100 m depth under the actual Permian surface as a function of denuded overburden thickness; values of k are for normal fresh water (data from Jetel 1969)

Hydrodynamic dispersion

This combined effect of molecular diffusion and mechanical dispersion usually does not have to be taken into account in usual groundwater modeling practice. It is almost sure that in case of gravity-forced infiltration we will have to deal with a very slow groundwater movement, which emphasizes molecular diffusion effect.

Gelhar, Welty and Rehfeld (1992) compiled various hydraulic dispersivity estimations. Based upon the selection of the most reliable data (Tab.3) we suggest to assign hydraulic permeability values ranging from 0.5/0.05 to 5/0.5 A_L/A_T to Permocarboniferous sediments in a kilometer-order observation scale. As for the crystalline bedrock - in terms of aquifer size, the data at smaller scale may seem to be higher for fractured media, but in view of a low reliability of the fractured rock data, this difference is of minimal significance (Gelhar, Welty and Rehfeld 1992). Hence similar values of hydraulic dispersivity can be assigned to sedimentary and crystalline rocks.

ACKNOWLEDGEMENTS

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REFERENCES

Barron EJ, Fawcett PJ (1995) The climate of Pangea: A Review of Climate Model Simulations, In: Scholle PA, Peryt TM, Ulmer-Scholle DS (eds), The Rermian of Northern Pangea, Volume 1: Paleogeography, Paleoclimates, Stratigraphy, Springer, Berlin, pp 37–61

Blecha M, Martínek K (1997) Změny prostředí na rozhraní karbonu a permu a jejich dopad na společenstva organismů ve fosiliferních obzorech podkrkonošské pánve, Závěrečná zpráva projektu GAČR 205/94/0692, Praha

Gelhar LW, Welty C, Rehfeldt KR (1992) A critical review of data on field-scale disrersion in aquifers, Water Resour Res 28(7):1955–1974

Chlupáč I (2002) Geologická minulost České republiky, Academia, Praha

Ingebritsen SE, Sanford WE (1998) Groundwater in geological processes, Cambridge University Press

Chlupáč I, Štorch P (eds) (1992) Regionální geologické dělení Českého masivu na území České republiky, Čas Mineral Geol Praha, 37(4):257–275

Jetel J (1969) Vztah pórovitosti a propustnosti permokarbonských sedimentů v podloží české křídy k hloubce uložení, KDP, Praha

Kozdrój W, Krentz O, Opletal M (eds) (2001) Comments on the geological map Laussitz–Jizera–Karkonosze (without Cenozoic sediments). 1:100 000, Warsaw

Mareš S (1967) Kolektorské vlastnosti karbonských hornin v kladensko-rakovické pánvi podle karotáže, Kand dis práce, Praha

Mareš S (1968) Density and porosity of rocks in the Carboniferous Kladno-Rakovník basin and their relationship to compaction, Čas Mineral Geol, Academia, Praha, pp.391–404

Menning M (1995) A Numerical Time Scale eor the Permian and Triassic Periods: An Integrated Time Analysys, In: Scholle PA, Peryt TM, Ulmer-Scholle DS (eds), The Permian of Northern Pangea, Volume 1: Paleogeography, Paleoclimates, Stratigraphy, Springer, Berlin, pp 77–97

Pešek J *et al.* (1998) Paleogeographic atlas, Late paleozoic and Triassic Formatioms, Czech Republic, Czech Geol Surv, Prague

Pešek J *et al*. (2001) Geologie a ložiska svrchnopaleozoických limnických pánví České republiky, Čes Geol Úst, Praha

Pešek J, Skoček Vl (1999) Alluvial–lacustrine red beds in Upper Paleozoic continental basins, Bohemian Massiv, Czech Republic, Czech Geol Survey Special Paper, Praha

Shneider JW, Roscher M (2000) Correlation charts, http://www.geo.tu-freiberg.de/palaeo/downloads.html

Hydrochemistry of the Shir-kuh granitoid hard-rock aquifer, Iran. Part 1: Spatial and temporal variations

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A b s t r a c t : Shir-kuh granitoid pluton is located in central Iran and several long and steep sloped valleys intersect this igneous body, forming in this way particular sub-basins. Three valleys (Sanij, Dehbala and Manshad) have been chosen to investigate the hydrochemical properties of this hard-rock aquifer. Along these valleys, a number of Qanats and natural springs discharge the aquifer. Temperature, EC and pH of the water samples were measured in the field and major ions (Ca, Mg, Na, K, HCO_3, Cl, SO_4) and SiO_2 component in laboratory. Spatial and temporal studies of these parameters showed: Temporal variation of temperature is very low that proves a low thermal exchange between water and the environment, and represents a relatively deep reservoir with narrowed downward water bearing joints and fractures. The increasing trend of pH of the water samples with time indicates that weathering processes are developing in the medium. Silica amounts of the samples show a decreasing trend with time and a positive saturation index, which proves a deposition stage. Plots of silica vs. total dissolved solids show positive different slope for different valleys, which is considered to be related to spatial differences in the pluton characteristics.

INTRODUCTION

Evolution of water chemistry is the result of the mass transfer between interstitial water and rock-forming minerals. The mass transfer depends on several parameters involved in weathering processes (temperature, pH, mineralogical composition etc.), but also the residence time of water in contact with the rock.

According to Chebotarev (1955), groundwater chemistry tends to evolve to the sea-water composition and the anionic evolutionary sequence can be explained by two factors: mineral availability and solubility. Since the Cl^- and SO_4^{-2} ions are not significant part of the chemical composition of the igneous and silicate rocks, their evolution is not toward the Cl^- and SO_4^{2-} facies and Chebotarev sequence is not applicable to hard rock aquifers. In order to investigate this matter and study the water chemistry of the Shir-kuh granitoid hard rock aquifer, water samples from different water resources along the valleys from top to bottom are taken and analyzed for their chemical composition.

The results of geochemical analysis of water in silicate terrain can be interpreted in two ways: 1- using stability diagrams to determine the weathering secondary products and 2- mass balance equation that relates dissolved material to specific source and sink such as rainfall, change in biomass and weathering as described by following equation (Drever 1997):

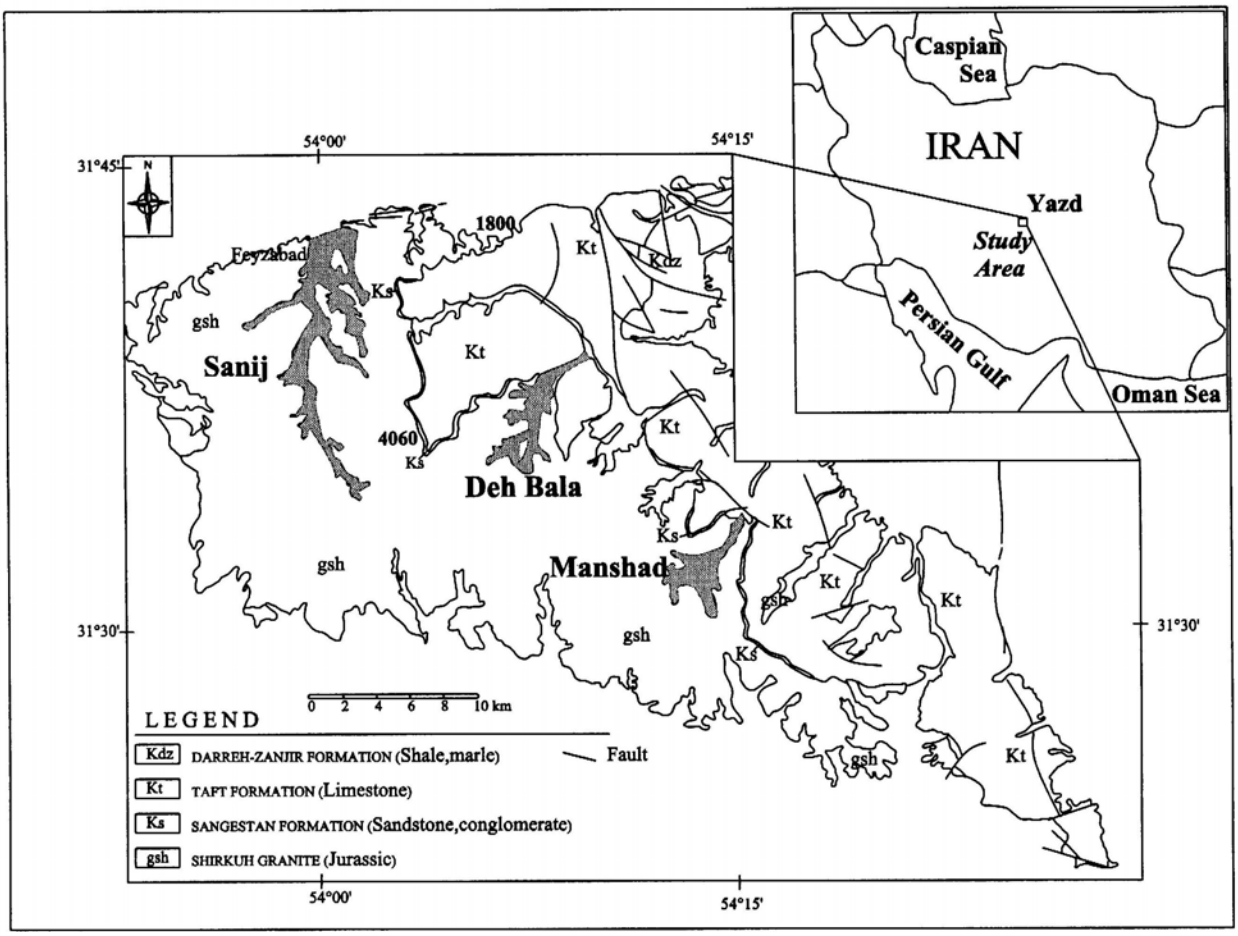

Figure 1. General geology map of the study area showing also the location of the valleys

Solutes in outflow =Solute from atmosphere + Solute from weathering ± Solute from change in biomass ± change in exchange pool

The last two parameters in the right hand side of this equation can be neglected if this is written for a long span of time (e.g. one year) as they reach equilibrium. As a result, the effect of weathering processes is identified and the chemical evolution of water is attributed to these processes.

GEOLOGICAL SETTING OF THE STUDY AREA

Shir-kuh pluton with an surface area of 1000 km^2 is located in central Iran (31° 23′ to 31°45′N and 53°50′ to 54°30′E). The main rocks of this pluton are granodiorite to monzogranite with the average mineral composition comprising of quartz (37%), An15-25 Plagioclase (34%), K-feldspar (18%), biotite (8%) and other minor minerals such as muscovite, pyroxen, chlorite and apatite. The pluton is partly overlaid by massive limestone of Taft Formation and Calcite as a secondary mineral is also present mainly in the fractures and fissures (Khalili 1997). Fig.1 shows the general geology of the area.

METHOD OF STUDY

Three valleys namely Sanij, Dehbala and Manshad located across Shir-kuh were chosen to investigate the hydrochemical properties of this hard rock aquifer. Along these valleys a number of Qanats dug by local villagers and a number of natural springs discharge the aquifer. Seven water samples were collected during April 2002 to February 2003. Temperature, EC and pH of the samples were measured in the field and major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-}, Cl^{-}, SO_4^{2-}) and SiO_2 in laboratory.

CONCLUSIONS

Results show that $HCO_3^{-}$and Ca^{2+} are dominant and SiO_2 ranges from 6 to 15 mg/L (average of 10 mg/L).

Temperature variation is high in the higher elevations but low in the lower parts. Difference in water table depth is thought to be the reason for the observed variations. EC and temperature also show an increasing trend toward the lower parts of the valleys due to longer travel distances.

Plots of silica vs. total dissolved solids show different slope for different seasons, with lower slope for wet season. Furthermore, due to spatial characteristic differences of this pluton, different positive slopes of the curves are observed for different valleys as indicated by Fig.2.

REFERENCES

Chebotarev II (1955) Metamorphism of natural waters in the crust of weathering. Geochim Cosmochim Acta 8

Drever J (1997) In: Saether O, Caritat P (eds) Geochemical processes, weathering and groundwater recharge in cathments, Balkema

Khalili M (1997) Petrography, mineral chemistry and geochemistry of Shir-kuh granite, south west of Yazd, central Iran. PhD thesis, university of Hamburg, 148p

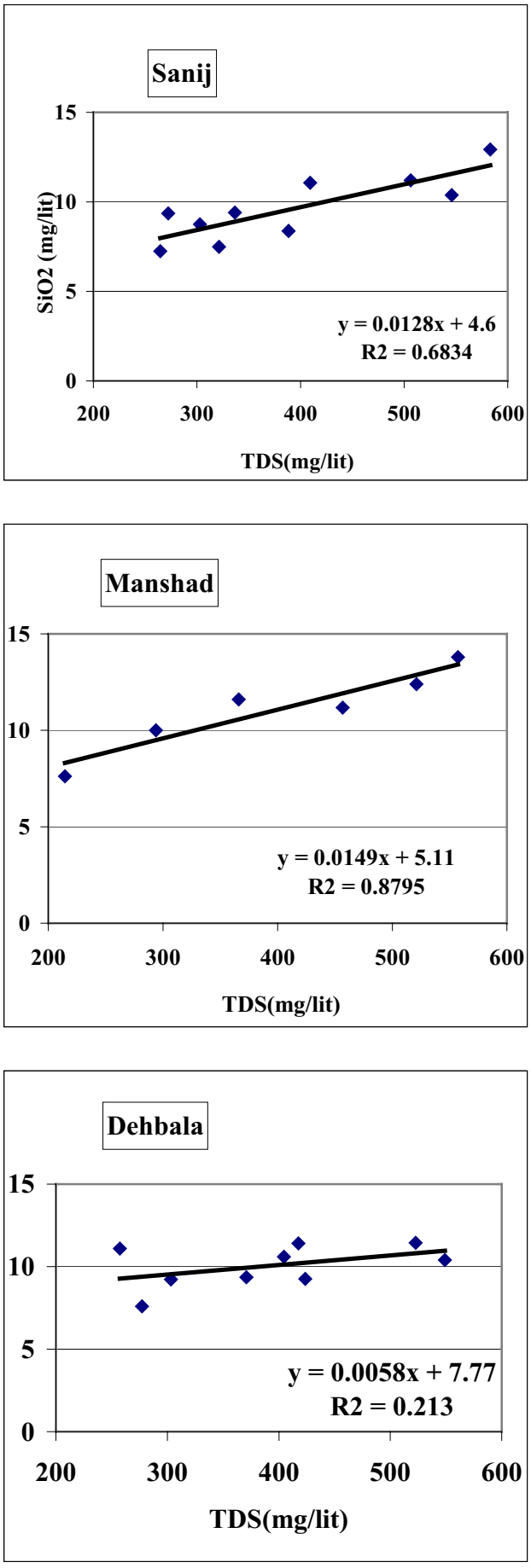

Figure 2. Silica vs. TDS content for different valleys (temporal average)

Hydrochemistry of the Shir-kuh granitoid hard-rock aquifer, Iran. Part 2: Mass balance study

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A b s t r a c t : Hydrochemistry evolution of natural groundwater is mainly affected by weathering processes, cationic exchange and biota effects. In order to study the effects of these processes on the chemistry of water in the Shir-kuh hard-rock aquifer in Iran, monthly water samples were analyzed for major ions and silica. The main rocks of this pluton are granodiorite to monzogranite with the average mineral compositions of quartz (37%), An15-25 plagioclase (34%), K-feldspar (18%), biotite (8%). A mass balance study is performed for this system using monthly data. It is observed that a number of ions such as K, HCO_3, SiO_2 remain as a positive or negative values at the end of the calculations. It is proposed that these residual values may belong to other processes such as cation exchange and/or biota effects. By examining spatial and temporal variations of these residuals the effect of other processes is investigated.

INTRODUCTION

High pressure and temperature minerals in the Earth's interior when in contact with dilute water on the earth surface become unstable and tend to transform into stable minerals. Weathering, that is the physical and chemical breakdown of primary rock and accumulation of secondary minerals as soil is a common phrase for this transformation.

In order to investigate the effect of weathering processes on the chemistry of water in a granitoid aquifer a mass balance study similar to that of Garrels and Mackenzie (1967) was carried out for Shir-kuh pluton in central Iran (31° 23′ to 31°45′N and 53°50′ to 54°30′E).

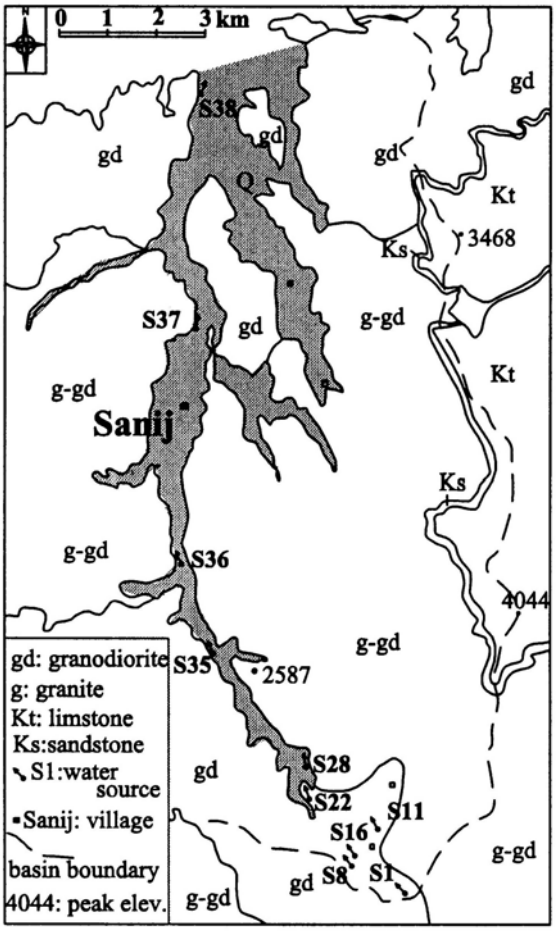

Figure 1. Sanij Valley and the position of different water resources

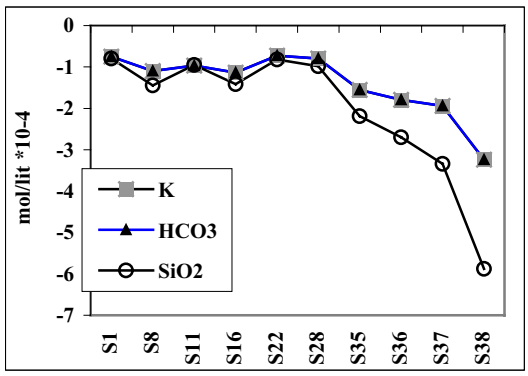

Figure 2. Residual of mass balance equation for different water samples along the Sanij valley

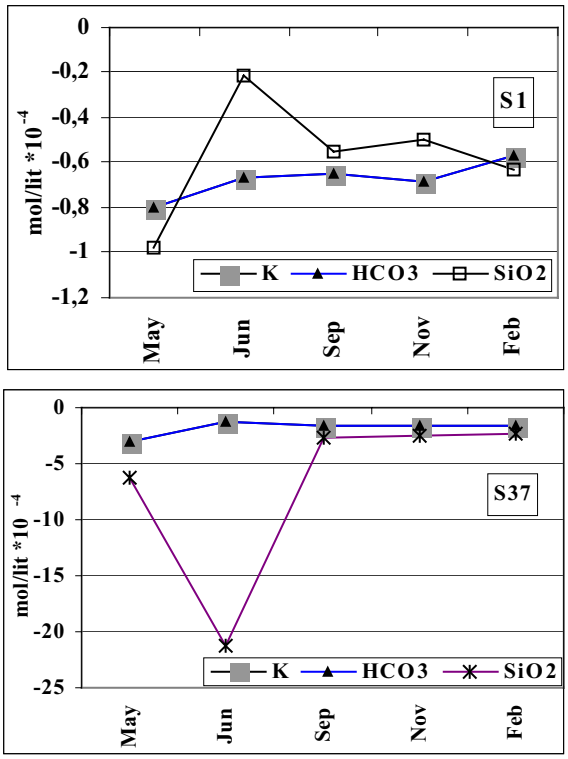

Figure 3. Residual of mass balance equation for S1 and S37 resources for different months (note that the values of K^+ and $HCO3^-$ coincidentally are equal)

METHOD OF STUDY

Three valleys located across the Shir-kuh pluton were chosen to investigate water resources chemistry and mass balance. The results of the largest valley (Sanij), which are similar to others, are presented here. Ten resources including springs and Qanats exist along this valley with S1 in higher elevation and S38 in the lower part (Fig.1). Water samples were collected several times during April 2002 to February 2003 and analyzed for their chemical composition. Tab.1 shows the average chemical parameters for the period. Stability diagrams (Drever 1988) are also prepared for annual average data of all water samples. Furthermore, mass balance equations are prepared using the data collected and the annual average data of the sampling period for S1 and S37 as well as annual average data for other samples. Since a very high correlation (R^2=0.9713) was found between Cl^- and Na^+ ions, it is considered that Cl^- is the result of NaCl dissolution. Similarly, SO^{2-}_4 is thought to be the result of gypsum dissolution as the XRD analysis of a sample of the soil of the area showed presence of small amount of gypsum.

CONCLUSIONS

Different stability diagrams show that all samples are in equilibrium with kaolinite secondary product suggesting that kaolinite is formed by the alteration of plagioclase and biotite of the granitoid.

The final result of the mass balance study for different resources along the valley in the form of residuals are zero for different components except for K^+, HCO^-_3 and SiO_2 which are negative as shown in figure 2. Decreasing trend of this curve (i.e. increasing deficiency) indicates that moving from top to the bottom of the valley in the direction of flow path in the aquifer, the weathering effect is replaced mainly by ionic exchange phenomena. Plot of these residuals for S1 and S37 for different samples during the study period is given in Fig.3. Based on this Figure, slight increase in the value of the residuals probably can be explained by decrease in biomass activity during the cold season.

REFERERENCES

Drever JI (1988) The geochemistry of natural waters, Prentice Hall

Garrels RM. Mackenzie FT (1967) “Origin of the chemical composition of some spring and lakes”. Equilibrium concepts in natural water systems. Am Chem Soc Adv Chem Ser 67:222-242

Sample	EC	TDS	pH	HCO^-_3	Cl^-	SO^{2-}_4	Na^+	K^+	Ca^{2+}	Mg^{2+}	SiO_2
S1	319.57	264.7	7.93	2.13	0.96	0.61	0.43	0.02	2.42	0.61	7.25
S8	329.25	302.9	7.45	2.38	0.98	1.00	0.60	0.03	2.30	0.88	8.75
S11	323.00	272.4	7.76	2.25	0.96	0.66	0.45	0.02	2.32	0.76	9.35
S16	396.25	336.5	7.54	2.73	1.15	0.88	0.56	0.03	2.88	0.90	9.40
S22	387.17	321.3	7.74	2.78	1.02	0.72	0.52	0.02	2.90	0.63	7.50
S28	464.40	388.5	7.45	3.11	1.37	1.03	0.68	0.03	3.52	0.72	8.38
S35	654.57	506.3	7.42	4.10	1.77	1.17	1.27	0.04	4.19	1.22	11.20
S36	544.50	409.3	7.55	3.16	1.51	0.98	1.19	0.04	3.17	1.37	11.06
S37	815.00	583.1	7.18	4.44	2.33	1.37	2.06	0.07	4.28	1.62	12.92
S38	759.14	546.0	7.53	4.04	2.40	1.39	2.04	0.05	3.19	2.29	10.38

Table 1. Chemical composition* of the Sanij valley water resources (annual average)

* Ions Concentration in epm, SiO_2 and TDS in mg/L and EC in micromohs/cm

TOPIC 4

INVESTIGATION AND INTERPRETATION METHODS IN FRACTURED ENVIRONMENT

- Location of fractured aquifers
- Field and laboratory methods, data interpretation
- Hydrogeologic mapping and data processing
- Well construction, aquifer and tracer tests, borehole geophysics

Using digital elevation model analysis to augment satellite and aerial photo interpretations

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A b s t r a c t : The use of remotely sensed imagery in groundwater exploration programmes is aimed at delineating linear surface features that reflect subsurface structural phenomena which control the flow and accumulation of groundwater. In many instances the utility of this remotely sensed imagery is limited by unavailability and ubiquitous cloud cover. In view of these limitations the analysis of digital elevation model (DEM) may be adapted as an alternative for lineament interpretation. Using a dynamic illumination technique at various azimuths over the DEM different linear features can be delineated. In this study the orientations of these inferred lineaments were found to correlate in direction to those delineated from aerial photo-interpretation of the same area.

INTRODUCTION

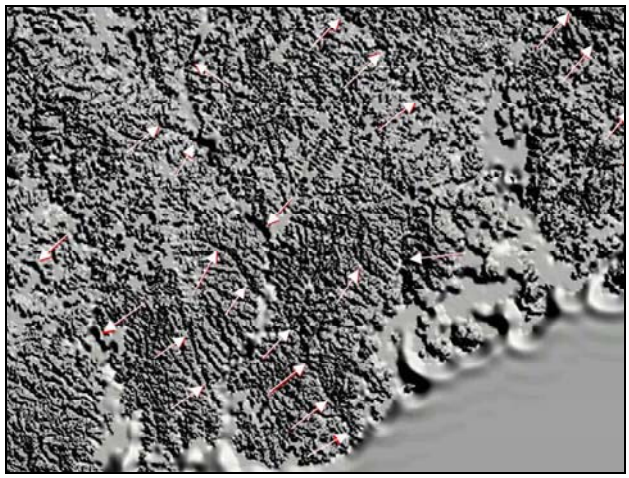
Groundwater exploration is most often preceded by the interpretation of remotely sensed imagery data such as satellite and aerial photographs. This is aimed at delineating linear surface features, which differ distinctly from the patterns of adjacent features and presumably reflect subsurface phenomena (Lattman and Parizek 1964; O'Leary *et al*. 1976). For example, the reflection of rock fractures, often emphasized in these imageries by persistent and controlled trending of topography, well-patterned drainage systems, vegetation and/or soil tonal alignments (Boyer and McQueen 1964). The importance of remote sensed data is also evinced by the successful use of such data to locate accurately subsurface structures important for governing recharge, migration, and discharge of groundwater (Fetter 1994; Brown 1994).

In most developing countries, however, the use of these remotely sensed imageries, particularly aerial photographs, are limited among other things by unavailability and ubiquitous cloud cover. Another general problem in the analysis of remotely sensed data includes the delineation of cultural features as geological lineament though these are often controlled with a follow-up ground-truthing. In view of these limitations an alternative means for lineament interpretation using digital elevation model (DEM) is proposed. The method has been used successfully as a complementary tool for the detection of lineaments from remotely sensed imageries in a hydrogeological study in parts of the Central Region of Ghana.

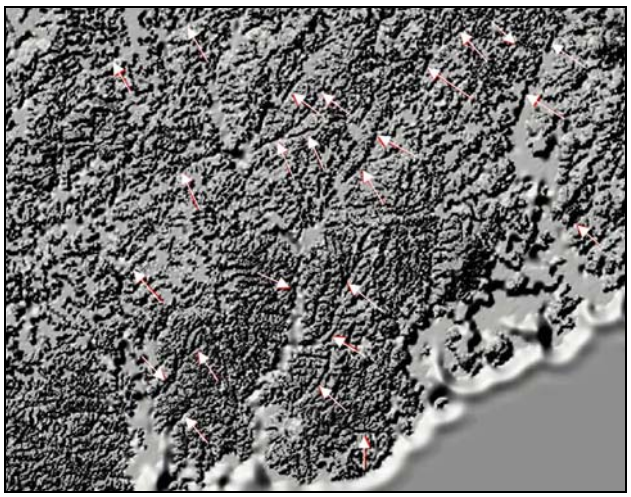
METHOD

Digital elevation modelling (DEM) is a GIS technique in generating 3-D terrain models. Its application in the basement crystalline terrains to analyse surface linear features is a new concept. The method involves the generation of 3-dimensional models from surface topographical data using appropriate geo-statistical technique such as the triangular irregular network or gridding among others.

The DEM of the study area was generated from digitised topographical data using a surface mapping software SURFER. The data, consisting basically X, Y representing the Eastings and Northings coordinates; and Z representing the spatially distributed elevation values, was gridded using the minimum curvature method. This was then transformed into a shaded relief image in which different effects were achieved by applying a dynamic shadowing technique with imaginary light source at an inclined angle to the horizon and at various angles of declination. These different declinations aided in generating shadows of linear features representing depressions most of which were inferred to be of structural significance due to their appearance in the shadowing processes. The models were vertically exaggeration to obtain the best brightness information of the shaded relief to identify and map subtle geo-topographic structures. The underlying concept of the shadowing and the vertical exaggeration is that the model will reflect the nature of the terrain for morpho-tectonic identification and isolation. This process emulates the techniques used for Side-Looking Airborne Radar (SLAR) data acquisition. Figs.1a and b represent shaded relief models of the dynamic shadowing with light sources at declinations of 45º and 315º respectively.



(a)



(b)

Figure 1 a, b. Shaded topographic relief under a light reflection at an inclination of 45º and a declination of (a) 45º and (b) 315º relative to the north. The arrows point to some of the detected lineaments

DISCUSSION

Lineaments were mapped on each shaded relief image during the various stages of the illuminations. About 529 lineaments were drawn; these were reduced to 380 through reproducibility analysis. The reproducible lineaments were then digitised and compared to an earlier set of lineaments delineated from limited aerial photographs covering the same area. It was observed that most of the DEM features coincide with the lineaments inferred from the aerial photo interpretations.

CONCLUSION

The use of digital elevation model (DEM) for a general lineament analysis proves to be an invaluable tool in complementing remotely sensed image analysis and even overcoming the limitations of cloud cover. Just as a Side-Looking Airborne Radar (SLAR) image it can also provide a unique perspective from which to observe geologically significant lineaments and their relationships to nearby geomorphic features.

The advantages of using DEMs for lineament mapping include the fact that there are no obscuring effects of cultural features that could be selected as lineaments as are occasionally the case in aerial photo interpretations. The adjustable illumination height and direction also allow for the maximum enhancement of selected lineament trends.

ACKNOWLEDGEMENTS

I am thankful to the Danish International Development Assistance - Enhanced Research Capacities (DANIDA-ENRECA) for sponsoring this study.

REFERENCES

Boyer R, McQueen J (1964) Comparison of mapped rock fractures and airphoto linear features. Photogrammetric Engineering and Remote Sensing 30(4):630-635

Brown N (1994) Integrating structural geology with remote sensing in hydrogeological resource evaluation and exploration. I:144-154. Tenth Thematic Conference in Geologic Remote Sensing, San Antonio, TX

Fetter CW (1994) Applied Hydrogeology-3rd Ed. Macmillan College Publishing Company, NY, 691 pp

Lattman LH, Parizek RR (1964) Relationship between fracture traces and the occurrence of groundwater in carbonate rocks. Journal of Hydrology 2:73-91

O'Leary DW, Freidman JD, Pohn HA (1976) Lineament, linear, lineation: Some proposed new definitions for old terms. Geological Society of America Bulletin 87:1463-1469

Using permeability to estimate vulnerability to diffuse pollution on fractured aquifers in Scotland

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A b s t r a c t : Due to the spatial variability in permeability of fractured aquifers it is difficult to ascribe a value to a particular aquifer type. This variability is significant for estimating vulnerability to point sources of pollution, but in estimating catchment scale vulnerability to diffuse pollution the spatial averaging of this permeability may yield a general aquifer value. A stochastic approach applied to field scale pumping test data from Scotland is used to estimate a quantitative indicator of permeability that is general for a given aquifer type. The unit specific capacity has been selected as the most representative correlate to aquifer permeability based on previous use (Ahmed and de Marsily 1987, Kupfersberger and Blöschl 1995), its availability and lack of assumptions made in its calculation. The basic outline of our methodology is given in this extended abstract with the results of its application in the accompanying CD of proceedings.

INTRODUCTION

Descriptions of aquifer vulnerability in the British Isles are primarily related to the presence and thickness of drift (NRA 1992, Palmer *et al.* 1995, Environment Agency 1998, SEPA 1997 and DoE for Northern Ireland 1994, 1999) or subsoil thickness and permeability (DoELG *et al.* 1999) over potential aquifer bedrock. Following this the permeability of the unsaturated subsurface geology is the most important vulnerability indicator. In Scotland and Northern Ireland the drift and subsurface geology have been classified as highly permeable, moderately permeable and weakly permeable and combined with soil classes to form groundwater vulnerability classes (Lewis *et al.* 2000).

The aquifer classification into three qualitative categories is an acknowledgement of the difficulty in characterising the permeability for the fractured and karstic flow regimes predominating in these regions. To ascribe a hydraulic conductivity for these aquifers would assume they are statistically homogeneous at a large scale, and hence an effective hydraulic conductivity could be defined at that scale. Stochastic methods are most suitable for calculation of the effective permeability where only an approximate knowledge of the aquifer system is assumed as they take a probabilistic view (Renard and de Marsily 1997).

Considering the vulnerability of the aquifers to contamination it is unlikely that a point source would be at a scale proportionate to the correlation length for a stochastic determination of the effective permeability. However, can a quantitative permeability indicator be calculated for these aquifers at a scale relevant for mapping diffuse pollution?

METHOD

The scale for vulnerability mapping of diffuse pollution depends on the resolution of available data such as climate, land use, soil physical properties and agricultural practice (Anthony *et al.* 1996). For example in the U.K., a mapping grid of 1 km^2 cells has been used in constructing a tool to support the U.K. governments policy development on diffuse nitrate pollution (Lord and Anthony 2000).

The term effective hydraulic conductivity, K_{ef}, can be defined in a stochastic context for the bulk permeability of a medium that is statistically homogeneous on the large scale (Renard and de Marsily 1997). If the fracture geometry (fracture spacing, length and aperture) are such that the spatial change in hydraulic conductivity follows a log-normal distribution, K_{ef}, will be equal to the geometric mean of the range of conductivities. It is assumed that the geometric mean of a parameter linearly correlated to hydraulic conductivity is also representative of the medium.

For a grid unit size of 1 km^2 the appropriate length scale of measurement is 10^2-10^3 m. For fractured media K_{ef} is most appropriately defined by large-scale flow and pressure head measurements (e.g. pumping tests, de Marsily 1986).

We have reviewed available data on pumping tests conducted in Scotland and correlated the locations with the associated geology type from the British Geological Survey (BGS) 1:625,000 digital map of solid geology.

From the most commonly available parameters in the pumping test data the specific capacity has been selected as the most representative measure of bulk permeability. However as the specific capacity is proportional to transmissivity (e.g. Logan 1964) rather than hydraulic conductivity, the unit specific capacity (*USC*) is derived instead, where:

$$USC = \frac{Q}{(h_0 - h_t)} \cdot \frac{1}{(h_0 - h_w)}$$

Q is the flux (m^3/d), h_0 the rest piezometric head height (m), h_t the piezometric head height after time t (m) and h_w is the height of the base of the pumped well (m).

The correlation of the specific capacity to aquifer transmissivity has been investigated by Ahmed and de Marsily (1987) who obtained a correlation coefficient of 0.87 for an aquifer in nothern France. Kupfersberger and Blöschl (1995) state that use of specific capacity data are useful in estimating the transmissivity fields in the context of groundwater quality modelling, particularly where channelised flow is to be expected.

Assuming the *USC* correlates with bulk aquifer permeability locally a general indicator value of permeability could be determined from the geometric mean of all the *USC* values associated with a particular geology type.

The resulting mean value will be an approximation depending on the range of locations and the total number of pumping tests, where the greater the spatial coverage and number of tests the better the approximation.

DATA

A key task in this work is collation and formatting of the pumping test data available for Scotland based on published reports and information archived by the BGS. At the time of writing a set of 71 tests had been identified in total, some of which do not include sufficient information to determine *USC*. Currently all of the tests cover 14 geology types of which only Devonian Old Red Sandstone and Permian basal breccia

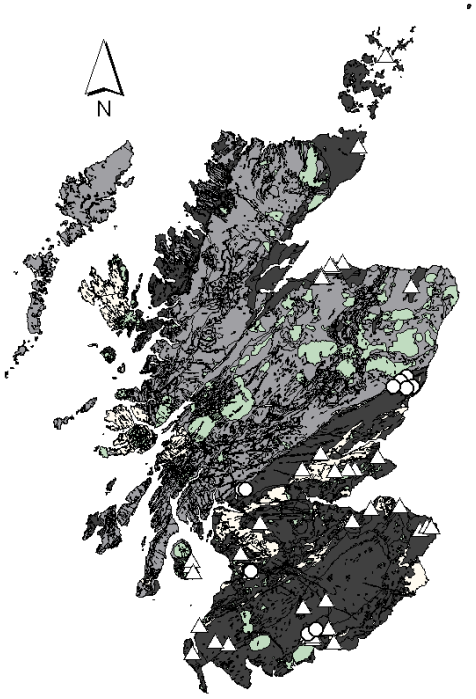

Figure 1. The 1:625,000 solid geology map of Scotland overlain with the sites of the pump tests (triangles) and those pump tests with specific capacity values (circles)

sandstones have specific capacity values from a significant number of tests (10 and 5 respectively).

Fig.1 shows the distribution of the initially identified pumping tests where the darker, mostly lowland, areas represent the sedimentary rock types and the lighter highland areas the metamorphic and igneous rocks. As can be seen the majority of the tests are associated with the lowland sedimentary deposits comprising mostly Devonian and Permian fractured sandstones.

The final database of pumping tests identified in this study is used to determine general permeability indicator values for the major fractured aquifers in Scotland. The results of which are given in the main paper included on the CD of conference proceedings.

REFERENCES

Ahmed S and de Marsily G (1987) Comparison of geostatistical methods for estimating transmissivity using data on transmissivity and specific capacity. Water Resour Res 23:1717-1737

Anthony S, Quinn P, Lord E (1996) Catchment scale modelling of nitrate leaching. Aspects of Applied Biology 46:23-32

de Marsily G (1986) Quantitative Hydrogeology: Groundwater Hydrology for Engineers. Academic Press Inc, London, 464 pp

Department of the Environment and Local Government, Environmental Protection Agency and Geological Survey of Ireland (1999) A scheme for the protection of groundwater. Geological Survey of Ireland, Dublin

Department of the Environment for Northern Ireland (1994) Groundwater vulnerability map for Northern Ireland. Environment Service, Department of the Environment for Northern Ireland

Department of the Environment for Northern Ireland (1999) Policy and practice for the protection of groundwater in Northern Ireland: a consultation document. Environment Service, Department of the Environment for Northern Ireland

Environment Agency (1998) Policy and practice for the protection of groundwater. HMSO, London

Kupfersberger H, Blöschl G (1995) Estimating aquifer transmissivities – on the value of auxiliary data. J of Hydrology 165:85-99

Lewis MA, Lilley A, Bell JS (2000) Groundwater vulnerability mapping in Scotland: modifications to classification used in England and Wales. In: Robins NS, Misstear BDR (eds) Groundwater in the Celtic Regions: Studies in Hard Rock and Quaternary Hydrogeology, Geol Soc Spec Pub No. 182, London

Logan J (1964) Estimating transmissibility from routine production tests of water wells. Ground Water 2(1):35-37

Lord EI, Anthony SG (2000) MAGPIE: A modelling framework for evaluating nitrate losses at national and catchment scales. Soil Use and Management 16:167-174

National Rivers Authority (1992) Policy and practice for the protection of groundwater. NRA, Bristol

Palmer RC, Holman IP, Robins NS, Lewis MA (1995) M A Guide to Groundwater Vulnerability Mapping in England and Wales. HMSO for National Rivers Authority

Renard Ph, de Marsily G (1997) Calculating equivalent permeability: a review. Advances in Water Resources 20 (Nos 5-6):253-278

Scottish Environment Protection Agency (1997) Policy No. 19. Groundwater Protection Policy for Scotland. SEPA, Stirling

Multivariate statistical approach for characterizing flow and transport processes

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A b s t r a c t : We propose a multivariate statistical approach for the analysis of meso-scale flow and transport experiments. Within this statistical approach flow and transport measurements are classified by means of quasi-homogenous groups in order to determine properties and parameter zonation controlling the governing flow and transport processes within the investigated system. The methodology was applied to a data set of gas flow and tracer experiments conducted to an unsaturated, fissured sandstone block of 60 × 60 × 60 cm^3 in size. The performed classification shows that the experimental data can be divided into three characteristic groups reflecting the main zonation of the investigated sandstone block. Furthermore, by the statistical analysis it can be shown that the texture and the bedding of the matrix are dominating the investigated system, as the fissures do not have an evident influence.

INTRODUCTION

Typically, fissured and fractured rocks are dominated more by heterogeneity and anisotropy than unconsolidated sediments, thus flow and transport can be expected to be more complex in such aquifer systems. As a consequent, the reliable characterization of fissured and fractured hard rocks and predictions of flow and transport in such rocks are very difficult due to their higher degree of heterogeneity and anisotropy. This characteristically causes high contrasts in hydraulic conductivity within the system and high spatial parameter variability. In order to determine the spatial variability of flow and transport parameters within fissured rocks unique experimental and interpretations techniques are required.

The goal of the proposed statistical approach is to conduct a rigorous and objective classification of results from flow and transport experiments which allows the identification of parameter zonation in terms of structure identification. The approach is illustrated by flow and transport data obtained from high-resolution gas flow and gas tracer experiments conducted to a fissured sandstone block. In order to ensure the objectivity and the possibility to transfer the approach to field experiments no a priori information about the investigated system are used. The classification is performed using a combination of different multivariate statistical procedures conducted to a set of defined variables describing the result of each experiment.

METHODOLOGY

The methodology was applied to data from a set of flow and transport data conducted in an unsaturated fissured cubic sandstone block of 60 × 60 × 60 cm^3 in size. In order to obtain fully controllable boundary conditions the block was sealed with epoxy resin of approximately 5 mm thickness. To enable access to the sample 96 injection and measuring ports, respectively, attached in a regular grid onto the cylinder. The ports consist of circular metal plugs with 3 cm in diameter defining controlled input / output areas. In the center of each plastic plug a valve was attached allowing to plug in a tube. The transport experiments discussed in this paper are conducted by using one port for injection and the port on the opposite side for extraction of the tracer. The distance between the opposed ports in each experiment is 60 cm. Thereby compressed air is injected into the unsaturated sandstone block through one port and the flow rate is measured at the port at the opposite block face using a mass flow meter. After a stationary flow field is established, a gas tracer (helium) is injected via a bypass loop and is detected by a mass spectrometer. Thus, 48 measurements were performed. In order to verify the following statistical classification, a detailed geological surface mapping of the investigated sandstone block was conducted (Fig.1).

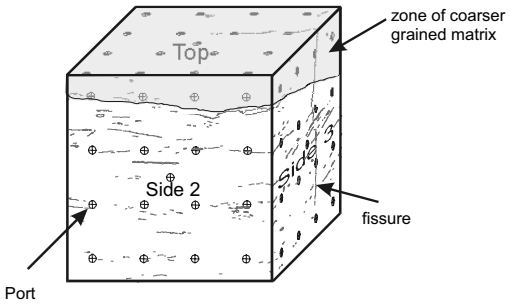

Figure 1. Diagram of the fissured block (0.216 m3) illustrating the fissure network and the zone of coarser grained matrix

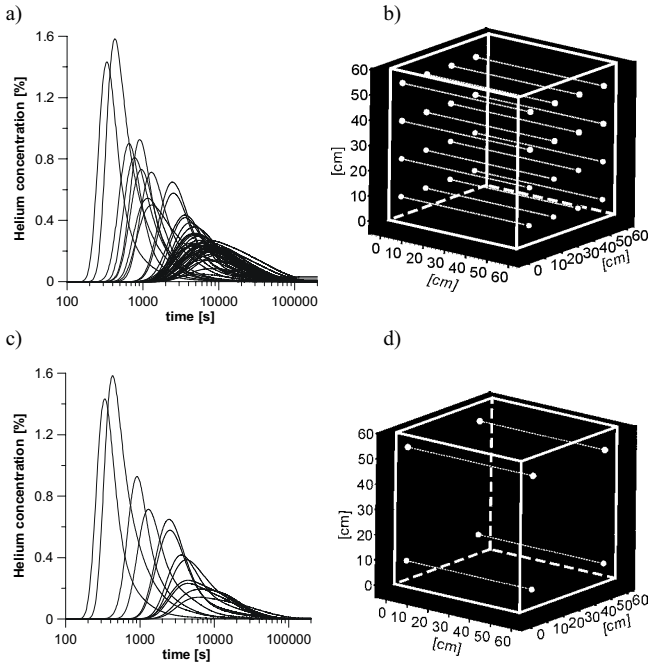

Figure 2. (a) Recorded breakthrough curves of all 48 tracer experiments conducted to the sandstone block. (b) Illustration of the 16 used port-port connections for one of three spatial directions. Note that for each flow and transport experiment only one of the shown configuration is used. (c) Illustration of the breakthrough curves separated with respect to their spatial position of the port-port configuration (d) Illustrates the port-port connections for the breakthrough curves illustrated in (c) for one of three spatial directions

The cubic shape of the block and the regularly arranged ports (Fig.2b) allow the separation of the experimental results into three groups with exactly the same measuring configuration. Without fundamental assumption about the structure of the block leading to restricted interpretations, it is not possible to remove the influence of the measuring condition on the breakthrough of the tracer. To account for this, the presented statistical methods are conducted separately for each of the three distinct measuring configurations. The interpretation are presented only for the experiments with the measuring configurations shown in Figure 2c, and 2d, respectively.

To ensure the objectivity of the approach, variables are chosen that can directly be derived from the experimental data, such as definite breakthrough times or measured flow rate. Consequently, the statistical approach described in this paper is based on the measured flow rate and the recorded breakthrough curves. In order to describe the run of the curves, the time of the mass-quartiles were chosen. The spread of the curve is described by the quotient from the times of 60% decile and the 10% decile with respect to the recovery of the injected tracer.

The statistical approach can be divided into two parts. The objective of the first part of the statistical investigations is i) to determine the number of variables that are sufficient to describe the investigated system and ii) to identify uncorrelated variables describing the flow and transport system of the cubic sandstone block. Uncorrelated variables are a prerequisite for the following classification of the breakthrough curves. For this reason, a combination was developed combining the results of hierarchical cluster analysis (Hartigan 1975) and principal component analysis (Jöreskog *et al.* 1976). The objective of the second part is the splitting of the breakthrough curves in quasi-homogenous groups by the determined uncorrelated variables. This allows the identification and characterization of representative data sets, reflecting different zones with quasi-homogenous flow and transport properties within the sandstone block. The classification is performed by means of k-means cluster analysis (McQueen 1969).

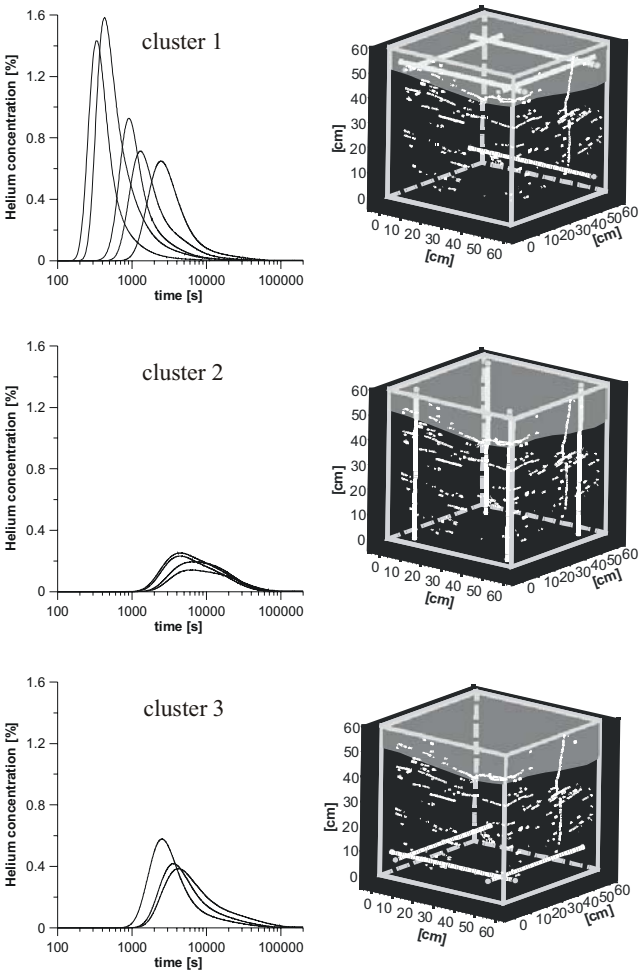

Figure 3. Classification results from the k-means cluster analysis of the breakthrough curves imaged in Fig.2c

RESULTS

The performed classification shows that the experimental data can be divided into three characteristic groups reflecting the main zonation of the investigated sandstone block. In order to verify the statistical classification the geological surface mapping and the spatial position of the ports of the conducted experiments are used. Fig.3 illustrates the three clusters and the spatial position of the ports of the conducted experiments.

Cluster 1 contains all breakthrough curves recorded from direct connections to the upper part of the cubic block which consists of a coarser grained matrix. One of the five breakthrough curves of cluster 1 was measured for a port-port connection in the lower fine grained part of the block. A more detailed mapping of the petrofabric shows that also in the vicinity of these port the matrix is coarser. Cluster 2 contains all breakthrough curves which are recorded orthogonal to the bedding and cluster 3 contains all breakthrough curves which are recorded parallel to the bedding in the finer grained matrix. The shape of the curves within the distinct clusters corresponds also well with the petrofabric derived from the mapping of the block. E.g., the breakthrough curves of cluster 1 are characterized by an initial and dominant breakthrough occurring at significantly earlier times with a sharp concentration increase up to the peak, while the breakthrough curves of cluster 2 and 3 are characterized by a broad and flat shape. This indicates that the upper part is dominated by well interconnected pores with a higher permeability than the lower part, as the fissures do not have an evident influence.

The nearly perfect conformity between the statistical and the geological classification demonstrates that the presented multivariate statistical approach is highly reliable. One application of the approach is to develop an adapted model including solely information gathered from the proposed approach.

ACKNOWLEDGEMENTS

The investigations were conducted with the financial support of the German Research Foundation to the “Hard Rock Aquifer Analogue: Experiments & Modeling” project under grant no. DI833/1.

REFERENCES

Hartigan JA (1975) Clustering algorithms, John Wiley & Sons, Inc New York, 315 pp

Jöreskog KG, Klovan JE, Reyment RA (1976) Geological Factor Analysis. Elsevier, Amsterdam, 178 pp

McQueen J (1967) Some methods for classification and analysis of multivariate observations. 5th Berkeley Symposium on Mathematics, Statistics and Probability 1:281-298

Identification of the diffusivity distribution by using a new hydraulic tomographic approach derived from travel time tomography

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A b s t r a c t : We propose a hydraulic tomographic approach which is based on the tomographic travel time inversion of pressure or hydraulic signals. The approach follows the procedure of seismic ray tomography. The similarity between these two techniques allows the use of the same inversion technique. The methodology was applied to data from a set of crosswell pressure tests conducted in an unsaturated fractured sandstone cylinder with a height of 34 cm and a diameter of 31 cm. The travel time inversion was conducted by using the SIRT-algorithm (Simultaneous Iterative Reconstruction Technique) with an included ray bending module. It was possible to reconstruct a three dimensional image of the diffusivity distribution of the cylinder and to verify the results by geological surface mapping.

INTRODUCTION

Reliable transport and groundwater models require detailed information about the spatial distribution of hydraulic conductivity and storage coefficient. Therefore, high resolution aquifer characterization techniques are needed. Hydraulic tomography has been proposed by several authors (Butler *et al.* 1999, Gotlieb and Dietrich 1995) as a method which allows the identification of the spatial distribution of hydraulic properties. The procedure consists of a series of hydraulic short-term tests conducted in a tomographical array. The arrival times obtained from these tests can be inverted numerically in order to produce a detailed two or three dimensional image of the hydraulic properties of the subsurface.

The presented hydraulic tomographic approach employs a new inversion technique derived from travel time tomography. Travel time tomography can be described as a one dimensional back projection of travel times of a two or three dimensional velocity distribution. The influence of the velocity field on the travel time between a source and a receiver can be described as a line integral relating the travel time to the velocity field. In accordance to this, it is possible to define a line integral relating the arrival time of a "hydraulic signal" to the diffusivity of the investigated system. This kind of line integral can be solved for hydraulic data by using algorithms which are established in several geophysical disciplines. On the basis of ray tomography we propose a methodology to invert travel times of pressure pulses in order to create a 3-dimensional image of the diffusivity distribution of a fractured sandstone cylinder. We use the terminology hydraulic instead of pneumatic tomography because the practical application of this method is the high resolution characterization of aquifers.

METHODOLOGY

The propagation of a pressure pulse in the subsurface can be described by a line integral relating the arrival time of a "hydraulic signal" to the reciprocal value of diffusivity which was developed by Vasco *et al.* 2000,

$$\sqrt{t_{peak}(x_2)} = \frac{1}{\sqrt{6}} \int_{x_1}^{x_2} \frac{ds}{\sqrt{D(s)}} \qquad (1)$$

where t_{peak} is the travel time of the peak of a signal from the point x_1 (source) to the observation point x_2 (receiver) and D is the diffusivity.

The propagation of a seismic signal can be described similarly by a line integral relating the travel time t, recorded between a source and a receiver, with the spatial velocity v distribution of an investigated area:

$$t = \int_{x_1}^{x_2} \frac{ds}{v(s)} \; . \qquad (2)$$

In our approach we utilize the similarity between the equations (1) and (2). This similarity allows the use of the same inversion software. The inversion was conducted with the commercial software package GeoTom 3D, which is based on the last Bureau of Mines tomography program 3DTOM (Jackson and Tweeton 1996). The program uses a least square solution of a linear inverse problem. The defined integral can be converted to a discrete inverse problem by approximating the integral as a summation as follows

$$\sqrt{t_i 6} = \sum_{j=1}^{n} \sqrt{\frac{1}{D_j}}\, d_{ij} \qquad (3)$$

where d_{ij} is the distance of streamline i in voxel j and D_j is the average diffusivity of the streamline along the path segment d_{ij} within voxel j. The goal of the inversion is to choose a diffusivity distribution which minimize the differences between the predicted travel times and the measured travel times. In according to this two equations can be defined

$$\Delta\sqrt{t_i 6} = \left[\sqrt{t_i^m 6} - \sqrt{t_i^e 6} \right] = \sum_{j=1}^{n} \Delta\sqrt{D_j^{-1}}\, d_{i,j} \qquad (4)$$

where $\Delta\sqrt{t_i 6}$ corresponds to the difference (error in data fit) between the measured travel time t_i^m and the estimated travel time t_i^e and $\Delta\sqrt{D_j^{-1}}$ is the incremental diffusivity correction. Additionally, a minimum criterion can be defined subject to (4) allowing the determination of a unique solution.

$$f\left(\sqrt{D_j^{-1}}\right) = \sum_{j=1}^{N} \left(\Delta\sqrt{D_j^{-1}} \right)^2 \rightarrow \min \quad . \qquad (5)$$

After Dines and Lytle 1979 (5) corresponds to a minimum energy correction. By minimizing (5) subject to (4) leads to the searched residual (difference between the square root of measured and calculated travel times) of each streamline:

$$\Delta\sqrt{D_j^{-1}} = \frac{\sqrt{\Delta t_i 6}\, d_{ij}}{\sum_{j=1}^{N} d_{ij}^2} \, . \qquad (6)$$

As the incremental diffusivity correction $\Delta\sqrt{D_j^{-1}}$ is accumulated for all streamlines before being applied to the voxels the used algorithm is called SIRT, Simultaneous Iterative Reconstruction Technique (Gilbert 1972). As the propagation of streamlines and seismic waves follows the same paths we can use seismic ray tracing techniques.

The proposed methodology was applied to data from a set of crosswell pressure tests conducted in an unsaturated fractured sandstone cylinder with a height of 34 cm and a diameter of 31 cm. In order to obtain fully controllable boundary conditions the cylinder was sealed with epoxy resin of approximately 5 mm thickness. To enable access to the sample 32 injection (source) and measuring (receiver) ports, respectively, attached in a regular grid onto the cylinder. The ports consist of circular metal plugs with 3 cm in diameter defining controlled input / output areas. In the center of each plastic plug a valve was attached allowing to plug in a tube. 487 measurements where performed. Fig.1 illustrates the experimental setup. At the injection port we have applied a Heaviside source. Thereby compressed air is injected into the unsaturated sandstone block and the flow rate is recorded depending on time at the measuring port. Prior to the resin coating the fractured sandstone cylinder was mapped in order to determine the potential position of the fracture.

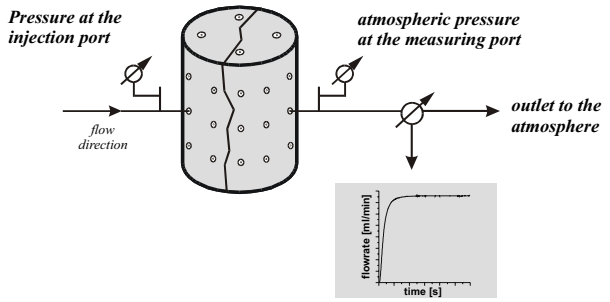

Figure 1. Experimental setup

For technical reasons a Heaviside source is easier to be put in practice, especially for the realisation of an adequate signal strength needed for long distances. In order to avoid the differentiation of each recorded curve a conversion factor relating Heaviside and Dirac sources is developed. The peak time of a signal with a Dirac source at the origin is equivalent to the time of a signal with a Heaviside source at the origin when 8.36 % of the maximum signal strength (steady state) is reached.

The described setup developed for laboratory investigation can be easily transformed to the field by using multi level packer systems.

RESULTS

The cylinder is characterized by a fracture ranging from top to bottom. The fracture is embedded in a more or less homogeneous matrix and it can be assumed that in this setting pronounced preferential flow may be observed. The potential position of the fracture was mapped prior to the resin coating of the cylinder (Fig.2). In order to minimize the effects of the space dependent streamline density we have confined our investigation area of the central part of the cylindrical sample (z_{min} = 6 cm, z_{max} = 27 cm) because the angular aperture covering the top and bottom is limited.

The imaged slices of different depths of the cylinder show the 3-dimensional spatial diffusivity distribution (Fig.2). The generalized parameter of diffusivity is the quotient of hydraulic conductivity to storage. The diffusivity is a suitable parameter for the characterization of differences in the flow and migration paths because they accentuate the contrast between the fracture and matrix dominated system. All slices show that significant variations in diffusivity are present whereby the largest diffusivity values coincide perfectly with the potential position of the fracture. The diffusivity distribution agrees with the well known fact that fractures usually have larger diffusivity values due to their higher conductivity and lower ability of storage.

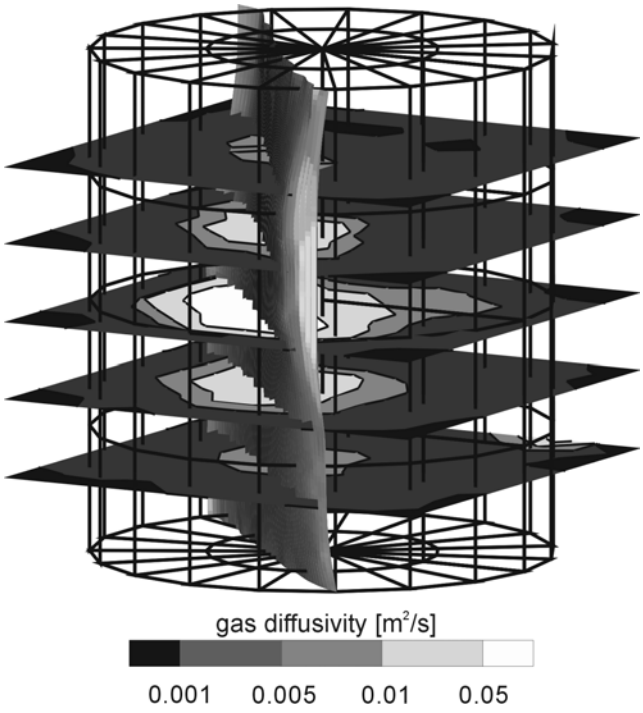

Figure 2. Illustration of the 3-dimensional image of the diffusivity distribution of the fractured sandstone cylinder and the potential position of the mapped fracture

The inversion was conducted with ten curved ray iteration steps whereby the initial fit to the measured data is based on a uniform preliminary. As the images were found to be highly reliable and robust it is planned to transfer this approach to the field.

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REFERENCES

Butler Jr.JJ, McElwee CD, Bohling GC (1999) Pumping tests in networks of multilevel sampling wells: Motivation and methodology, Water Resources Research 35(11):3553-3560

Dines KA, Lytle RJ (1979) Computerized Geophysical Tomography, Proc IEEE 67(7):1065-1073

Gilbert P (1972) Iterative methods for three-dimensional reconstruction of an object from projections. J theor Biol 36:105-117

Gottlieb J, Dietrich P (1995) Identification of the permeability distribution in soil by hydraulic tomography. Inverse Problems 11:353-360

Jackson MJ, Tweeton DR (1996) 3DTOM: Three-dimensional Geophysical Tomography, United States Department of the Interior, Bureau of Mines, Report of Investigation 9617, 84 pp

Vasco DW, Keers H, Karasaki K (2000) Estimation of reservoir properties using transient pressure data: An asymptotic approach, Water Resources Research 36(12):3447-3465

Application of the oriented core drilling/sampling method to environmental site investigations

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In the environmental consulting industry, the oriented core method has important applications for sedimentary bedrock sites with complex structure and stratigraphy. These complex subsurface features could include sedimentary rock strata which are heavily fractured or faulted and/or possess variable bedding thickness, lithology, and continuity and provide contaminant migration pathways in the vadose and/or saturated zones. The acquisition of bedrock core is, in itself, a considerable benefit for any subsurface investigation because the consultant is able to view a nearly intact undisturbed rock record of the drilled subsurface. The collection of continuous oriented core provides an even greater advantage for an environmental or geotechnical investigation, because it allows the geologist to view and analyze the formation structure and subsequently prepare a detailed subsurface geologic model. Subsurface data obtained from previous or subsequent investigations, using less expensive conventional drilling techniques, then can be input into this model with a high level of confidence.

A case study documenting the use and results of the oriented core investigation method is presented to summarize the overall methodology and procedures, advantages/disadvantages of the method, and the resultant data and interpretation. The subject environmental case history involves a gasoline remedial investigation at a site located in Los Angeles, California. Thinly interbedded to laminated, poorly to moderately indurated, sedimentary rock, with moderately developed fractures of the Miocene-age Puente Formation underlies the site (Dibblee 1989; Lamar 1970).

Data generated from seven oriented coreholes were used to provide ”anchor points” for detailed 2- and 3-dimensional stratigraphic evaluations. The site stratigraphy typically consists of an upper coarser-grained, lithofacies predominantly composed of finely interbedded sandstone, siltstone, and silty mudstone in the south part of the site. This lithofacies is underlain by either a relatively thick and more massively bedded sequence of silty mudstone/clayey siltstone, mudstone, and siltstone in the central part of the site, or a lower variably bedded lithofacies dominated by sandy siltstone/silty sandstone in the north part of the site. Bedding continuity is highly variable; in most cases, individual beds were shown to be continuous over distances no greater than 50 to 100 feet. Individual bed thickness typically varies from less than 1 foot to more than 5 feet. Bedding orientation is relatively uniform across the site with a mean orientation striking N79°W and dipping 25°SW; this mean orientation is consistent with the regional bedding orientation (Dibblee 1989; Lamar 1970).

The site hydrostratigraphy, which consists of thin permeable sandy lamina interbedded with impermeable mudstone and siltstone, is conducive to the formation of small-scale isolated groundwater flow and storage zones. The bedrock and fractures are capable of storing appreciable quantities of groundwater due to their generally higher porosity, but transmit water slowly and in small volumns. Groundwater at the site flows generally southward in a down-dip direction. This relationship suggests that higher permeability strata within the formation play a significant role in controlling groundwater movement. These conditions favor groundwater recharge of permeable beds that dip beneath less permeable confining beds, thereby creating local pockets of higher potentiometric pressure. Pressure gradients are relieved and groundwater equilibrates where high-angle fractures intersect these locally confined beds.

Numerous fractures were observed during the logging and analysis of bedrock samples; in some places, the fracture density exceeded 4 fractures per 10 linear feet of borehole. Visible fracture aperture ranged widely from no visible aperture to apertures exceeding 10 mm. The majority of bedrock fractures occurs within the vadose zone and uppermost saturated zone at depths less than 40 feet below grade. Significant fracturing above 20 feet is present, but oriented data above this depth could not be obtained due to the magnetic influence of metallic aboveground equipment. The fractures were grouped into three distinct sets. The most prevalent fracture set is composed of north-south trending, near-vertical fractures. A second, somewhat less common, east-west trending, high-angle fracture set and a third, least prevalent, low-angle, northwest-southeast trending fracture set that parallels bedding orientation.

The structural and lithologic information obtained from the oriented core was integral to developing a conceptual model for gasoline contaminant transport at the site. The model was based on a dual-porosity transport system, whereby gasoline migration occurred both within isolated permeable beds and through interconnected fractures of varying geometry and extent. The strong similarities in the depths where gasoline-bearing fractures occur, as well as the close correspondence of these fractures to the water table in the center of the investigation area, demonstrate the local ability of fractures to store gasoline and suggest that fractures are serving as local migration pathways. Near vertical, crosscutting fractures appeared to facilitate hydraulic interconnection between these otherwise isolated permeable beds. These fractures permitted the fuel hydrocarbons to migrate via a laminae-fracture-laminae sequence across more impermeable bedding thus providing the necessary transport mechanism by which the hydrocarbons migrated. These findings were consistent with estimates of hydraulic conductivity, which also suggest that most of the fuel hydrocarbon transport at the site occurs within permeable laminae and, to a lesser extent, fractures.

REFERENCES

Dibblee TW (1989) Geologic map of the Los Angeles quadrangle, Los Angeles County, California, Dibblee Geological Foundation, Santa Barbara, California, 1 sheet, scale 1:24,000

Lamar DL (1970) Geology of the Elysian Park-Repetto Hills area, Los Angeles County, California, California Division of Mines and Geology, Special Report 101. San Francisco, California, 45 pp

Hard-rock hydrogeology of the Alentejo Region (South Portugal): new cartography based on results of the "ERHSA" Project

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Abstract: Between 1997 and 2001 a Project called "Study of the Groundwater Resources of Alentejo Region" (ERHSA, in portuguese) was carried on in the region of Alentejo, southern part of Portugal. Specifically, the University of Évora was in charge of almost all Alentejo hard rocks, except for the limestone metamorphic rocks. During ERHSA Project more than 7,000 water points were inventoried in hard-rock aquifers. This extended study allowed to confirm some previous aquifer features, namely regarding the Gabbros of Beja Aquifer System, and to detect new productive or potentially productive areas within the region, namely the aquifer systems of Campo Maior and Elvas Charnoquites, Pavia-Mora and the Évora-Montemor-Cuba. The two latter systems are built mainly on gneissic or gneissic-migmatitic rocks, metamorphic volcanic-sedimentary complexes and some tonalitic rock.

INTRODUCTION

Between 1997 and 2001 a Project called "Study of the Groundwater Resources of Alentejo Region" (ERHSA, in portuguese) was carried on in the region of Alentejo, southern part of Portugal (fig.1). This Project was coordinated and financed by the Coordination Commission of Alentejo Region, a governmental regional organization and was executed by three more institutions.

Specifically, the University of Évora was responsible by the investigation on almost all Alentejo hard rocks (igneous and metamorphic rocks), except for the limestone metamorphic rocks.

More than 7,000 water points were inventoried in all hard rock aquifers of Alentejo during this period. Most of them are wells or large wells that are used basically for agriculture or domestic purposes. The most important abstractions are clearly related with agriculture.

INVESTIGATION METHODOLOGY

This work was based on the collection of all the well execution reports that the different drilling companies working in Alentejo region have done since the begining of its activities. This information was later confirmed by field data, to eventually correct or confirm some suspicious original data, namelly related with yield measurements, litological logs, etc.

In order to compare the different hard rock lithologies in terms of hydrogeological productivity, the yield values registered on the reports where considered very important. These yields were obtained by pumping tests using compressed air directed to the bottom of the well, which causes the total head draw down. So, it is not a recommended exploration yield, but a value that can be compared with any other data obtained by the same procedure, and must be seen as instant yield values (Carvalho 2000; Mira and Chambel 2001). In this case, only the data from deep wells was considered. The unproductive wells were also inventoried.

In terms of the geological features, the definition of the new aquifer systems was also based on the geo-structural divisions of Alentejo.

RESULTS

Generally the hard rock aquifers of this area are considered of low productivity (exception made for the crystalline limestones). Metamorphic and igneous rocks represent most of the Alentejo area, with only a few meters of weathered layers (0 to 6 m deep) and a very incipient fracture system under these layers. More deeply, the bedrock has only a very large net of fractures. In igneous rocks the wells have generally some water on the first 60 m deep, and rarely occur new productive levels under this deepness. In metasedimentary rocks the probability of occurrence of new deep productive levels increases, being equally possible to get water for instance on the first 100 m or on the following 100.

Figure 1. Alentejo region in Portugal

Even so, an aquifer with special characteristics was already known in Alentejo (fig.2): the Gabbros of Beja Aquifer (Paradela and Zbyszewski 1971). This bibliography refers 40 to 50 m of weathered or fractured gabbro-dioritic rocks, with the groundwater flowing in fractures that are enlarged by chemical water attack. In 1971, in this aquifer, large wells with maximum of 20 m deep, much of them with galleries in the bottom, and other wells with maximum of 50 m deep, were used to abstract groundwater for human supply. The yields could reach 8 L/s, exceptionally 10 L/s, with the production clearly decreasing during the dry season. More recently Duque (1997) had shown that the productivity, for 132 well data, was about 5 L/s (mean), 3.15 L/s (median) till a maximum of 36 L/s. The high productive levels vary between 1 and 78 m deep, being the major productive levels between the 12 and 20 m. Based on 185 well logs, the aquifer shows a mean of 3.5 m of topsoil clays, a total weathered layer of 22 m and a fractured deepness till 50 m.

During the execution of ERHSA Project, the informations had confirmed the existence of other aquifer systems with similar characteristics (ERHSA 2001). One of the main conclusions was that the gabbroic rocks, the gneisses, the migmatitic gneisses, some volcano-sedimentary and tonalitic rocks were more productive than the remain lithologies of the region.

The hydrological studies had detected three new aquifer systems (fig.2), now designated as:

- Campo Maior and Elvas Charnoquites, gabbroic metamorphized rocks, extremely weathered, separated in two different spots;
- Pavia-Mora, gneissic granitic rocks;
- Évora-Montemor-Cuba, divided in 5 sectors (Évora, Montemor, Escoural, Cuba-S. Cristóvão, Vidigueira-Selmes), essentially based on gneisses, migmatitic gneisses, acid and

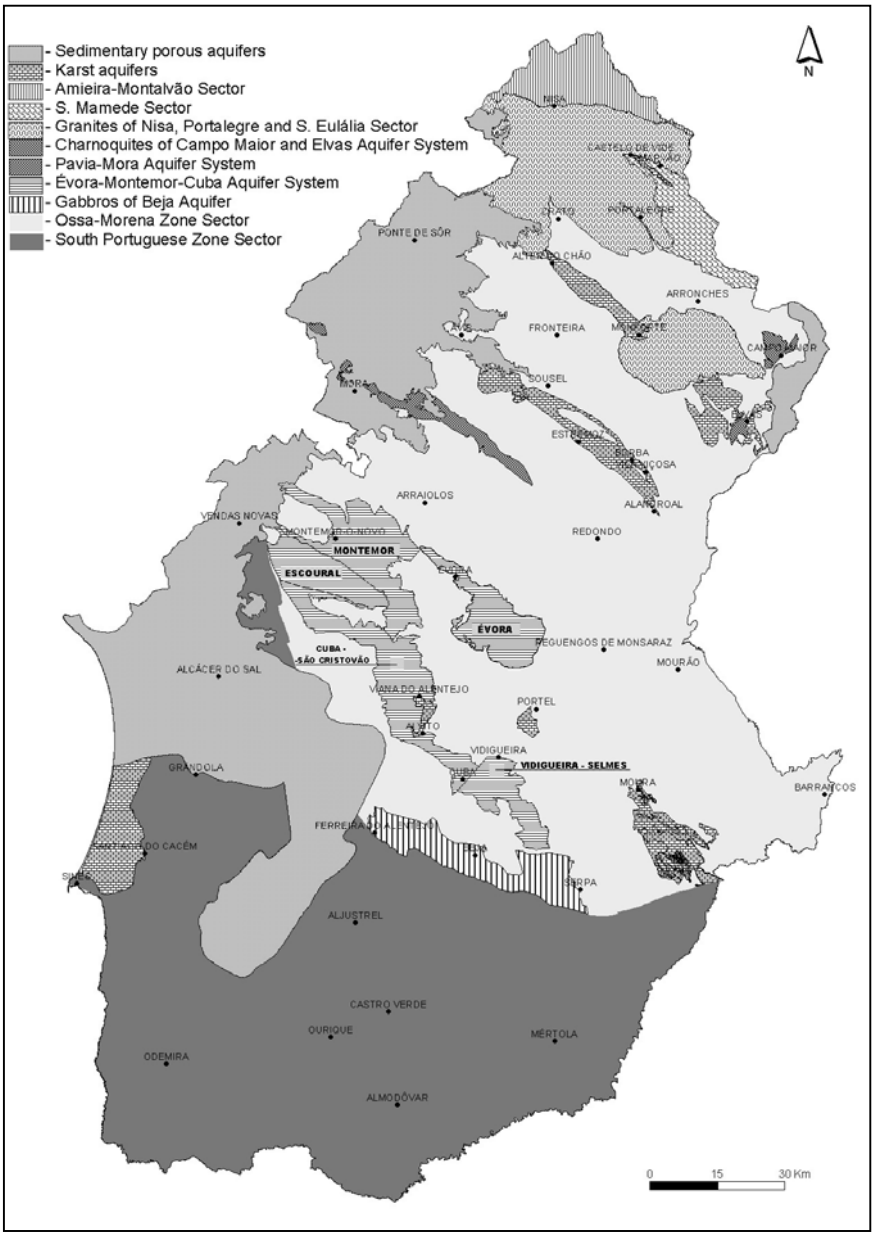

Figure 2. New hydrogeological cartography of Alentejo region (Portugal)

basic volcanites and some tonalitic rocks.

On the remaining areas, some low productive sectors were identified (fig.2):

- Amieira-Montalvão, mainly schists;
- S. Mamede, mainly schists;
- Granites of Nisa, Portalegre and S. Eulália, granitic rocks;
- Ossa-Morena Zone, mainly schists and granitoid rocks, but also volcanic or porphyritic rocks;
- South Portuguese Zone, mainly schists, greywackes and volcano-sedimentary complexes.

The results show that the most productive aquifers have a mean of instant yield values higher than to 4.50 L/s and median values superiors up to 2.74 L/s (Gabbros of Beja Aquifer and Évora and Vidigueira-Selmes sectors of the Évora-Montemor-Cuba Aquifer System).

The Montemor and Escoural sectors of the Évora-Montemor-Cuba Aquifer System and also the new identified aquifer systems of the Charnoquites of Campo Maior and Elvas and Pavia-Mora have mean instant yield values of more than 3 L/s. Only the Cuba-S. Cristóvão sector seems to have lower values; however the extension of the area, the relatively lack of information and the similar lithologies with other sectors had allowed to suppose identical hydrogeological characteristics.

The low productive sectors of Amieira-Montalvão, S. Mamede and of the Granites of Nisa, Portalegre and S. Eulália show mean instant values less than 2 L/s, the last one with only 0.65 L/s.

The low productive sectors of Ossa-Morena Zone and South Portuguese Zone display mean values respectively of 2.01 and 2.42 L/s, which mean that in these sectors there are some more productive areas.

Dividing the yield by the deepness of the wells, the same conclusion is possible: the Évora sector (gneisses and tonalites) and the Gabbros of Beja Aquifer have clearly higher productivities (more than 0.12 L/s/m drilled) when compared with Escoural, Vidigueira-Selmes and Montemor sectors (more than 0.03 L/s/m drilled). The other sectors, considered of low productivity, show generally values less than 0.02 L/s/m.

CONCLUDING REMARKS

The study allowed to confirm some previous aquifer informations, namely regarding the Gabbros of Beja Aquifer, and to detect new productive or potentially productive areas on this region, namely the aquifer systems of the Charnoquites of Campo Maior and Elvas, Pavia-Mora and Évora-Montemor-Cuba. There are also some field indicators that some regions of porphyries, considered in the low productivity area of the Ossa-Morena Zone can also be very interesting aquifers, namely where the fracturation is important.

It seems that the mainly aquifers are built on gabbros, gneissic or gneissic-migmatitic rocks, metamorphic volcanic-sedimentary complexes and some tonalitic rocks.

REFERENCES

Carvalho J (2000) The impounding groundwater project in cristaline formations: some clues (in portuguese). University of Évora, Évora

Duque J (1997) Hydrogeological characterization and mathematical modelling of the Gabbros of Beja aquifer (in portuguese). Master Thesis, University of Lisbon, Lisbon, 220 pp

ERHSA (2001) Project "Study of groundwater resources of Alentejo region (ERHSA, in portuguese). Coordination Commission of Alentejo Region, Évora

Mira F, Chambel A (2001) Productivity of hard rock aquifers in Alentejo region, South Portugal. In: Seiler, Wohnlich (eds) Proceedings of the XXXI IAH Congress: New Approaches Characterizing Groundwater Flow, Balkema, Lisse (Holand) 2:1035-1039

Paradela P, Zbyszewski G (1971) General hydrogeology of the centre and south of Portugal (in portuguese). Guide-Book of the excursion nº 9 of the I Hispano-Luso-American Congress of Economic Geology, General-Direction of Mines and Geological Services, Lisbon, 123 pp

The use of VLF-EM survey for hydrogeologic purposes in a porphyric unproductive hard-rock aquifer

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A b s t r a c t : In order to verify the suitability of the geophysical method Very Low Frequency (VLF-EM), and at the same time find groundwater to supply a large farm called Herdade da Apariça, a survey having used the ABEM (WADI) equipment was carried out in porphyric rocks of the northern part of Beja (South Portugal). The field works occurred in three areas previously defined by interpretation of aerial photography. The measurement was realised in 5 profiles with 1970 m width. The geophysical survey and hydrogeological research allowed to drill 5 boreholes, being 4 extraction wells and 1 piezometric well. The productivity of the abstraction wells were between 2,000 L/h and 10,000 L/h, which is a very good yield when compared with other yields previously obtained from wells inside this aquifer. VLF-EM proved to be an essential tool to increment the prosperity of drilling wells under these hydrogeologic conditions.

MAIN GOALS

The geophysical survey in hard-rock environment is widely used as a way to find groundwater under difficult hydrogeologic conditions (Milsom 1989).

The porphyric rocks occurring in the northern part of Beja city, are the most unproductive regional aquifer. The electromagnetic method VLF-EM (Very Low Frequency - Electromagnetic Method) is very helpful to identify fractured deep structures in hard-rock aquifers. In order to verify the suitability of this geophysical method and, at the same time to find groundwater to supply a large farm called Herdade da Apariça, a survey was carried out using this method of Very Low Frequency (VLF-EM) with ABEM (WADI) equipment in three large areas previously defined by interpretation of aerial photography. This areas were classified as zones which have relative hydrogeological potential. The measurement was realised in 5 profiles with 1970 m width

After the geophysical survey five wells were drilled in the most prospective areas to verify the efficiency of the method.

GEOLOGICAL, GEOMORFOLOGICAL AND CLIMATOLOGICAL SETTINGS

The Beja region is a region mainly built up by metamorphic and igneous Precambrian and Palaeozoic rocks, affected by the Hercynian Orogeny. The area under research (Herdade da Apariça) is placed in the southern part of a geostructural domain called the Ossa Morena Zone (OMZ).

Herdade da Apariça is placed in a porphyric SW-SE structure. This structure is surrounded by diorites (north) and gabbros (south). Geologically these formations are called as Igneous Complex of Beja (ICB) (Fig.1).

This area is placed in a very flat area. The region is influenced by the Mediterranean climate, with high temperature ranges (high temperatures in Summer and a very dry period between June and September), and is also considered as a semi-arid region with many desertification problems. The regional precipitation mean in forty years for this area is about 530 mm/year.

HYDROGEOLOGIC FEATURES

The porphyric rocks layered in the northern part of the Beja city (Alentejo region – South Portugal), are the most unproductive regional aquifer in the area. These rocks belongs to the most unproductive regional aquifer (Chambel and Duque 1999). Recently, Chambel *et al.* 2002 classified this rocks into the Ossa Morena Low Productivity Igneous and Metamorphic Rocks Aquifer System (OMLPIMRAS).

The regional aquifer log structure has usually an upper layer of 5 to 15 meters deep of weathered rock and a second layer build by fractures rock till 30 metres deep. Above this deep the probability to find groundwater is extremely low. It is a very superficial aquifer that usually accomplish the topographic surface, and is extremely dependent of the main source of recharge the annual precipitation. The groundwater use is essential for human purposes and here are used mainly for human and cattle supply. The mean of the aquifer yields are less than 1 L/s.

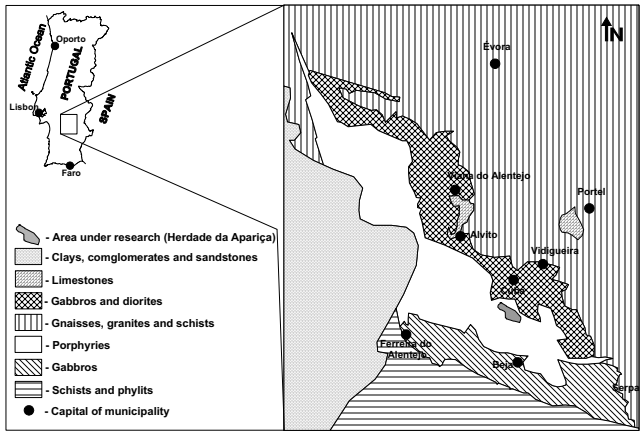

Figure 1. Location and geological features of the research area

VLF-EM SURVEY

The VLF-EM is an electromagnetic method that can be used to find steeply dipping structures that differ from their surroundings with regard to electrical resistance. This method is thus very well suited to water prospecting in fracture zones.

VLF-EM is based on the secondary fields created by electric conductive bodies in the ground, when stroked by a electromagnetic primary field. This low frequency field is sent out from a military radio transmitter, working generally in the frequencies between 15 and 30 kHz. In the Herdade da Apariça we worked with 20.9 kHz frequency with measurements each 5 m.Four groups of VLF profiles were performed in previously defined places. They are marked as grid P1, P2, P3 and P4 (Fig.2). Their location was chosen with the purpose of confirming in the field the existence of possible fractures already identified on the aerial photography

The cross sections and profiles shown in the figs 3 and 4 have are an example of VLF-EM results. They have also the location of the positions of the chosen drilled wells. The VLF-EM method allows to identify fractures that can not be observed on surface. In

this way, it complements the superficial observations, increasing the possibilities of success. The tab.1 shows the results of the four drilling wells and one piezometer (the less productive drill).

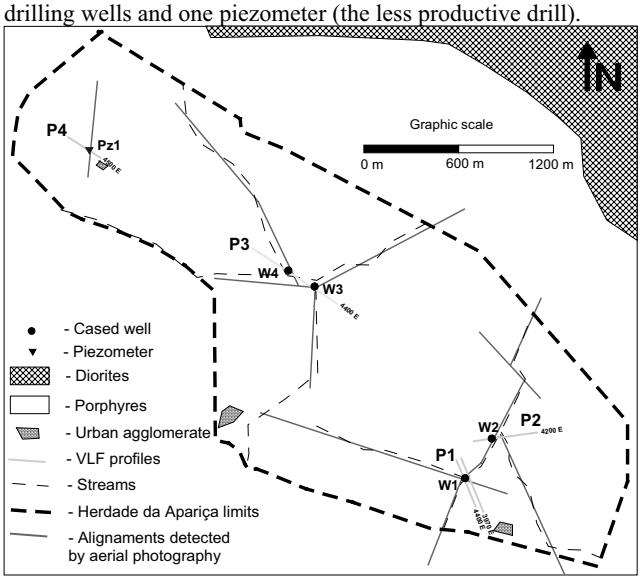

Figure 2. Location of the VLF profiles in the Herdade da Apariça and the drilled wells and piezometer

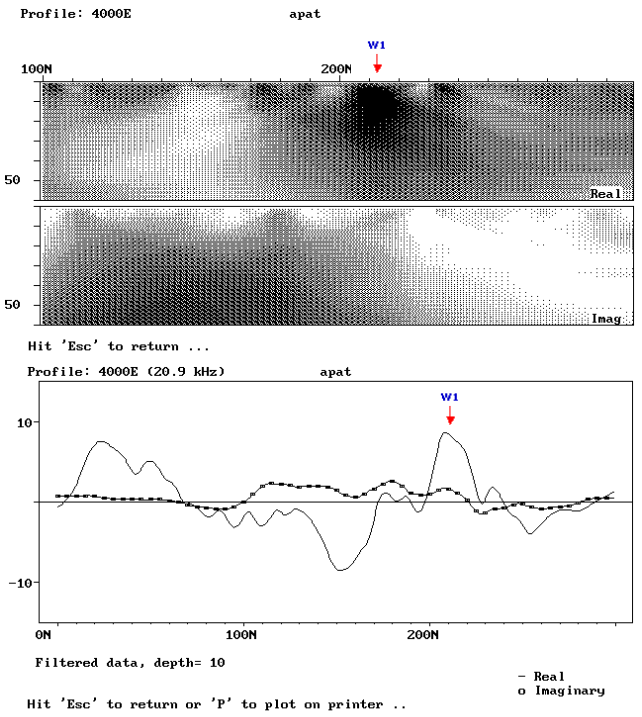

Figure 3. Profile P1 and location of the correspondent drilled well

Wells	Deepness (m)	Range of productive layer (m)	Yield (m^3/h)
W1	70	8 – 25	10,000
W2	66	5 – 22	4,000
W3	120	6 – 15 and 55 – 61	6,000
W4	55	7-15	5,000
Pz1	50	8 - 18	2,000

Table 1. Drilling and yield results got through VLF-EM method (wells and piezometer)

The yield productivity was get by air lift. The deepness of the anomalies detected by geophysics are correspondent to the range of the productive zones (very weathered and fractured). The well 3 has also a contribution of a more deep productive fracture that occurred between 5-61 m. Four boreholes were cased and will be used for groundwater supply and one will be used to piezometer purposes.

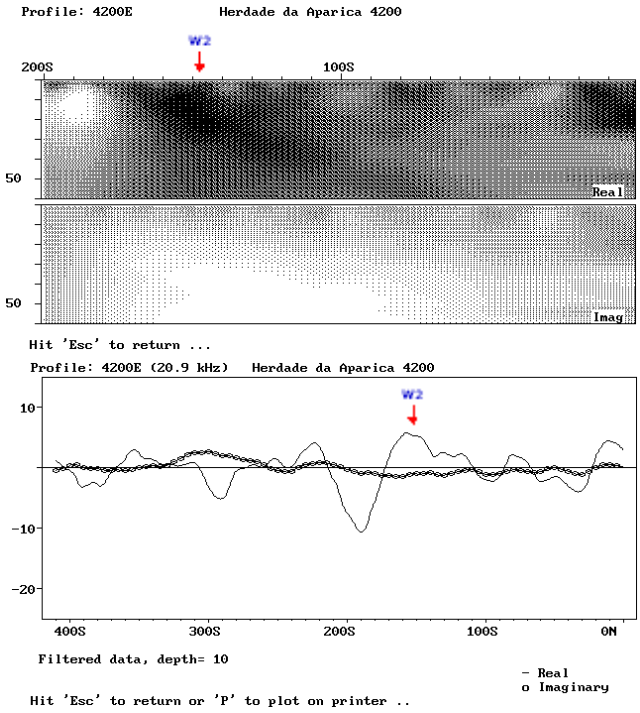

Figure 4. Profile P2 and location of the correspondent drilled well

CONCLUSIONS

The geophysic prospecting and hydrogeologic research allowed to drill 5 boreholes, being 4 extraction wells and 1 piezometric well. The yield productivity of the abstraction wells are between 2,000 L/h and 10,000 L/h, which is almost higher than the regional mean. It s a very good yield when compared with the other yield values get from wells inside this aquifer.

In the Herdade da Apariça the VLF-EM proved that in hard rock media (porphyries) works well and seems to be a useful tool to increment the tax success of drilling wells. However it but must be used carefully, due to the multitude of answers that can be achieved; the specialists must know very well the geology and structural history of the region to interpret correctly the geophysical results.

AKNOWLEDGEMENTS

J. Duque express his thankfulness to the University of Évora (Prof. A. Chambel) for the use of the VLF-EM ABEM.

REFERENCES

Chambel A, Duque J (1999) Hard rock aquifers of Alentejo region (South Portugal): Contribution to the water and land use management. In: Fendek M, Fendeková M.(eds) Proc XXIX International Association of Hydrogeologists – Hydrogeology and land use management 171-176

Milson J (1989) Field geophysics, John Wiley & Sons, New York. 182 pp

Chambel A, Duque J, Nascimento J (2003) Hard rock hydrogeology of the Alentejo Region (South Portugal): New cartography based on the "ERHSA" Project. In: Proc IAH International Conference on Groundwater in Fractured Rocks

Contribution to the development of groundwater resources in the Precambrian Oban massif, southeastern Nigeria, based on geoelectrical and hydrochemical data

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A b s t r a c t : Hydrogeological studies encompassing geoelectrical and hydrochemical tools were used to characterise the water bearing layers in the Oban massif. The results show that the area is characterised by two major aquiferous units. These units include an upper weathered layer and a lower fractured bedrock. Hydrochemical data show that most of the parameters considered important for drinking water purposes are within the WHO standards. The chemical facies include Ca^{2+}-HCO_3^- and Ca^{2+}-Na^+-$HCO_3^-Cl^-$ for the upper and lower layers respectively. Correlation analysis between formation resistivity and some water parameters (TDS, hardness, SAR) show good correlation. In general, the formation resistivity data are very good predictor of aquifer types, characteristics and water quality.

INTRODUCTION

The development of groundwater resources has been a major focus of past and present governments in Nigeria. Despite this, a lot of communities especially the rural population are yet to benefit. The present work is therefore to highlight some recent results on studies of groundwater development in parts of Precambrian Oban massif. The data focuses on aquifer delineation, characteristics and water quality using surface resistivity method.

The Oban massif is situated in southeastern corner of Nigeria (Fig.1). The region has a tropical climate with average annual temperature and precipitation of 26 °C and 300 cm. The dominant rock type in the area includes gneiss and schist of various types, including pegmatitic and quartizitic intrusives.

DATA ACQUISITION

The study involved field mapping, geoelectrical measurements and water analyses. During the geoelectrical survey, vertical electrical soundings (VES) using the schlumberger array were made in 14 communities (Fig.1). The conventional curve matching and use of auxillary point diagrams (Zohdy 1965), in addition to computer forward modelling were used to interpret the data. Groundwater samples were also collected for analyses after drilling and from existing boreholes and wells. Temperature, conductivity, total dissolved solids, pH, and dissolved oxygen were measured in the field. The major cations and anions were determined by means of atomic absorption spectrophotometer and ion chromatography.

RESULTS AND DISCUSSION

Geoelectrical properties

Results of vertical electrical sounding indicate two main aquiferous layers. These include an upper aquiferous layer and a lower aquiferous layer (Tab.1). The upper layer is characterised with an apparent resistivity (ρa) in the range 28 to 1800 ohm m (mean ~ 450 ohm m). The layer varies in thickness between less than 1 m to 140 m (mean ~ 20 m), Tab.1. This layer is composed of highly weathered through moderately weathered to slightly weathered materials. The materials of the upper layer are mostly silty, clayey lateritic materials at the top and sandy and gravelly materials at the bottom, which forms the boundary with the bedrock.

The lower layer is the bedrock with apparent resistivity in the range 1000 to < 5000 ohm m (mean ~ 2000 ohm m), Tab.2. Lower values (1000 to 3000 ohm m) indicate slightly weathered to fractured bedrock while higher values (> 3000 ohm m) represent fresh bedrock.

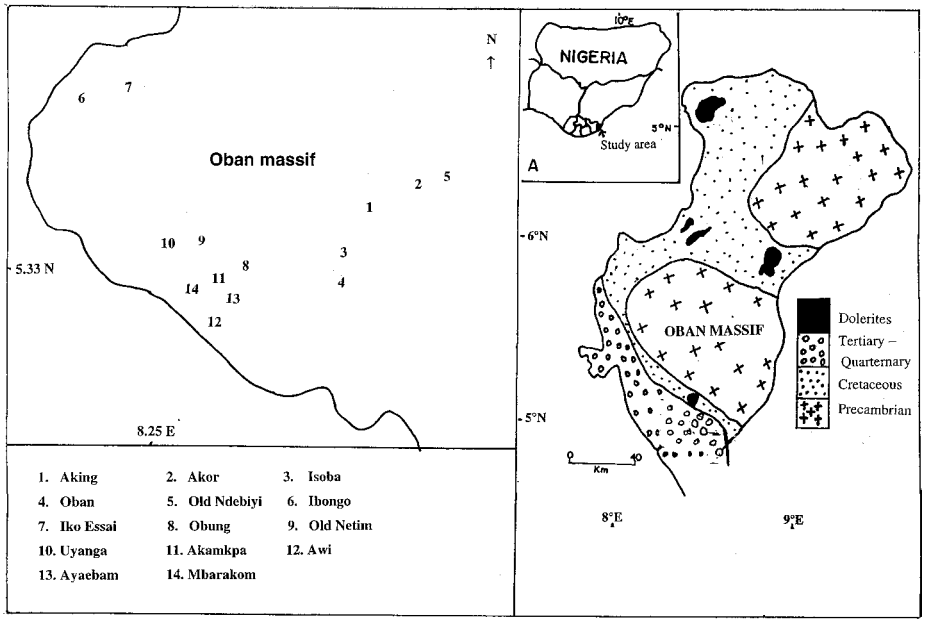

Figure 1. Map of parts of southern Nigeria showing Oban Massif and VES locations

Aquifer parameters and hydrochemical characteristics

Aquifer parameters including specific capacity and transmissivity were computed on the basis of the relation between specific capacity and apparent resistivity on one hand and between specific capacity and transmissivity on the other. The relationships are of the form: SC = 0.003R + 0.20 (Edet and Okereke in press) where SC is the specific capacity in m³/d/m and R the apparent resistivity in ohm m. The transmissivity is given by T = 86400(10Y-8.96) (Darko & Krasny 2000), where T is the transmissivity in m²/day and Y transmissivity index, expressed as Y = log (10^6C) where C is the specific capacity in m³/d/m. The values for the different layers are presented in Tab.1. The data show comparatively higher values for the lower fractured bedrock.

The results of the chemical analyses are summarised in Table 3 for the different layers. The groundwaters in both layers are acidic (pH < 7.00), soft (TH < 75 mg/L), and fresh (TDS < 1000 mg/L). Positive correlation at 95 % confidence limit (p = 0.05) show good correlation between ρa and TDS (r = -0.72, p = 0.004); ρa and total hardness (r = -0.63, p = 0.067); and ρa and sodium adsorption ratio (SAR) (r = -0.64, p = 0.066). This indicates that the quality of groundwater can be inferred from the values of apparent resistivity. Positive correlation between TDS and HCO_3^- (r = 0.40, p = 0.286) indicate that weathering of the rocks controls the water chemistry. This is also supported by the relatively higher concentrations of ions in the upper layer. On the basis of the Deutsch (1997) scheme, the groundwater in the area can be classified as Ca^{2+}-HCO_3^- and Ca^{2+}-Na^+- Mg^{2+}-HCO_3^--Cl^- for the upper and lower layers respectively.

IMPLICATIONS FOR GROUNDWATER DEVELOPMENT

The development of groundwater resources in such a basement terrain will depend on the proper definition of the aquiferous layers; estimation of aquifer parameters; and prediction of water quality. In the area, electrical resistivity has made the following possible: (a) Identification of two main aquiferous layers. These include an upper highly to slightly weathered layer and a lower slightly weathered to fractured bedrock; (b) Estimation of specific capacity and transmissivity and (c) Inference on the water quality based on the relationship between apparent resistivity and TDS, hardness and SAR. Thus from the above, aquifer resistivity can be used as a good predictor of the type of aquifer, the characteristics and water quality. Hence for future groundwater development, surface resistivity will be of immense importance before drilling.

CONCLUSION

This study describes the application of surface resistivity in the search for groundwater in a typical Precambrian basement rock terrain. The method gives a good prelude on the type and characteristics of the aquiferous layers and the quality of groundwater. Therefore surface resistivity method should be encouraged before the actual drilling for proper and effective groundwater development.

REFERENCES

Darko PK, Krásny J (2000) Adequate depth of boreholes in hardrocks: A case study in Ghana. In: Sililo et al (eds) Groundwater: Past Achievements and Future challenges, A.A. Balkema, Rotterdam: 121-125

Deutsch WJ (1997) Groundwater geochemistry: fundamentals and applications to contaminations. Lewis Publication 221pp

Edet AE, Okereke CS (In press) Hydrogeological and hydrochemical character of the regolith aquifer, northern Obudu plateau, SE Nigeria. Hydrogeology Journal

Zohdy AAR (1965) The auxiliary point method of electrical sounding interpretation and its relationship to the Dar-Zarrouk parameters. Geophysics 30:644-660

Table 1 Summary of geoelectrical and hydrogeological parameters for the aquiferous layers in Oban massif

Layer	Statistics	Apparent resistivity ohm m	Thickness m	Borehole well/depth m	Depth to water level m	Saturated thickness m	Specific capacity m³/d/m	Transmissivity m²/d
Weathered	Max	1800,00	140,00	60,00	10,50	50,00	3,20	303,15
	Min	28,00	0,30	2,00	0,10	1,50	0,50	47,40
	Mean	447,76	17,21	16,32	2,68	13,76	1,37	134,60
Bedrock	Max	4800,00		65,00	14,00	50,50	9,77	925,60
	Min	1040,00		45,00	4,00	41,00	4,22	400,00
	Mean	1991,47		52,88	7,33	44,94	5,95	563,88

Table 2 Summary of chemical data for the aquiferous layers in Oban massif

Layer	Units	Weathered			Bedrock			WHO
		Max	Min	Mean	Max	Min	Mean	
Temp.	°C	29,90	27,60	28,37	29,20	27,40	28,40	
TDS	mg/l	765,40	104,80	341,28	158,90	68,30	111,97	1000,00
pH		5,88	3,66	4,43	4,95	4,02	4,46	6,6-8,5
TH		133,23	4,19	48,34	51,88	10,06	22,36	< 75,0
Ca^{2+}	mg/l	36,40	4,77	15,20	12,02	2,41	5,90	50,00
Mg^{2+}	mg/l	10,30	0,48	3,98	4,85	0,62	1,77	100,00
Na^+	mg/l	32,36	5,92	17,23	7,95	3,00	4,39	200,00
K^+	mg/l	17,20	0,40	5,72	10,50	0,70	3,11	12,00
Cl^-	mg/l	43,39	3,99	18,35	35,50	1,62	9,31	250,00
NO_3^-	mg/l	82,00	8,87	29,32	30,00	10,29	15,68	10,00
SO_4^{2-}	mg/l	9,60	0,51	2,57	5,22	0,49	1,80	400,00
HCO_3^-	mg/l	154,95	23,94	69,68	39,04	5,02	19,32	
Facies		Ca^{2+}-HCO_3^-			Ca^{2+}-Na^+-HCO_3^--Cl^-			

A fractal dimension model for hydraulic parameter evaluation from single well pumping tests in fractured media

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A b s t r a c t : The author for analyzing single well production test data under variable discharge rate conditions has developed the fractal specific capacity approach. Pumping test data from wells drilled in a typical heterogeneous fractured and/or karstic medium usually present, among other things, discharge rate variations. Such variations affect time drawdown and time recovery curves thus complicating the well test analysis by conventional methods, which are only valid for constant discharge conditions. Under field conditions, the well specific capacity, $y(Q_t, s_t) = Q_t / s_t$, versus drawdown curve, may be approximated by a power law of the type $y(Q_t, s_t) \cong y^* = Q^* / s_t^D$, where Q^* is a uniform fractal discharge and D a fractal flow dimension. The *flow dimension* and *equivalent uniform fractal flow* concepts are basic tools for fractured media parameter evaluation and in that respect they are supposed to be the paper's main contribution to well hydraulics in fissured rocks.

Parameter identification through the proposed method is only provided in the pumped well for hydraulic transmissive parameters (*fracture transmissivity and fracture aperture, hydraulic conductivity and permeability*) and storage parameters (*porosity*) for the hydraulic conductor, namely for the well-block-fracture system. Physical properties for diffusion and elastic response (*diffusivity and storage coefficients*) as well as for delayed yield from the weathered zone to the lower fractured rock domain may only be evaluated by using a flow model in the (*r,z)* plane. This can be done through Boulton and Streltsova (1977) block-fracture model, by replacing the specific drawdown s / Q, for the inverse of the fractal specific capacity, $1 / y^*$.

The model has been applied for analyzing 86 drawdown curves and 75 recovery curves from pumping tests performed in 72 wells distributed over several groundwater Brazilian sub provinces and in two oceanic islands, namely Fernando de Noronha in Pernambuco and Roatán in Honduras. The author in karstic and fissured media obtained preliminary estimations of hydraulic properties. The order of magnitude for fracture apertures is in agreement with studies carried out in Germany in a highly permeable fault zone (Himmelsbach *et al.* 1994). The order of magnitude for porosity estimates are also in agreement with typical results for fractures in 60 m deep wells, which are on the order of 0,0050% (Snow 1968).

INTRODUCTION

In the semi arid region of northeastern Brazil Precambrian crystalline rocks occupy over 500.000 km². Given the frequent extended water shortage that results from droughts, groundwater development through wells in hard rocks is a common practice as a means of water supply in rural areas. Well depth usually ranges from 50-60 m with median discharge of about 2 m^3/h. Even though geophysical methods have been introduced in well location, the outcome of the drillings is over 20% of dry wells. Then, understanding fluid flow through fractured geological media seems to remain as a necessity to address this problem and hopefully improve well production capacity.

The ability of granular aquifers to store and transmit water is linked to a porous matrix of a geologic formation that is assumed to have known geometric parameters (thickness and aerial extent) and homogeneous hydraulic properties. These last properties in particular may be defined for a continuous porous medium through the REV (representative elementary volume) concept (Bear 1972).

In regard to hard rocks the ability to store and transmit water is linked mainly to fractures that represent (in relation to the original porous matrix) a secondary discontinuous porous or fractured system of channels. The generalization of the continuum approximation in this case is open to question given that the circumstances may require huge volumes of geological formation in order to obtain stable values of the domain properties. Guerin and Billaux (1993) propose a connectivity index to evaluate for a given size the validity of the continuous concept for flow by using statistical properties of a fracture field. Gustafson and Krasny (1994) pointed out significant differences between granular porous media and fractured media and suggested the denomination of *hydraulic conductor* to replace the term *aquifer* in fractured formations.

In the present approach the hydraulic conductor concept applies for the set {borehole + interconnected fractures + blocks + weathered cover} formed by the borehole, the blocks delimited by fractures directly or indirectly connected to the production well, and the fracture conduits through which water reaches the well. So, the parameters evaluated from a single well production test such as transmissivity, hydraulic conductivity, permeability, porosity and mean fracture aperture are assessed to characterize the hydraulic conductor. The hydraulic conductor is a *random sample point* of the hard rock regional "fissure aquifer" and the significance of these physical properties must be restricted to the well point itself. More explicitly, it is assumed that a well of depth z, drilled in a position (x,y) of a space occupied by fractured rocks, generates a random hydraulic conductor. In case the porous matrix of the blocks is not supposed negligible, the fractured media is double porosity; otherwise one can say it is simply a fractured media.

FRACTAL SPECIFIC CAPACITY

Efforts are generally made to maintain a constant discharge rate in step-drawdown tests since this is an important consideration during the data analysis. However, as observed in numerous single well production tests carried out in Precambrian fractured rocks in northeastern Brazil, no matter the efforts to preserve a constant discharge the pumping rate typically decreases with time. As a matter of fact water wells in the Precambrian region generally tend to dry out during long droughts. This behavior is interpreted as evidence that the hydraulic conductor's volume reservoir is finite in nature. But, given the circumstances attention was called for the necessity of evaluating the behavior of the hydraulic conductor under a uniform flow regime. The search for a constant discharge rate during test data analysis leads to a fractal well specific capacity approach, as explained in what follows.

A fractal set (Turcotte 1992) is defined by the expression

$$N_i = \frac{C}{r_i^D} \tag{1}$$

where N_i is the number of fragments or *boxes,* using the box counting method (Peitgen *et al.* 1992) in which an object can be

successively ($i = 1, 2, \ldots$) divided with a scaling factor r_i ; C is a constant of proportionality and D is the fractal dimension.

Consider a single well production test performed with variable discharge rate $Q_i(t)$ in a random hydraulic conductor. During the experiment of duration t_b a series of discrete measurements of discharge rate $Q_i(t)$ and of drawdown $s_i(t)$ is made with time t. By definition the specific capacity of the hydraulic conductor y_i [L^2/T], given by

$$y_i = \frac{Q_i(t)}{s_i(t)} \tag{2}$$

is a temporal discrete function $y_i(Q_i(t), s_i(t))$ of two variables. Let us assume that y_i may be approximated by a function y_i^* given by

$$y_i^* = \frac{Q^*}{s_i^D} = \frac{Q^*}{s_i^*} \tag{3}$$

where y_i^* is a fractal specific capacity [L^2/T]; Q^* is a fractal constant discharge $[L^{D+2}/T]$; $s_i^* = s_i^D$ is a fractal drawdown $[L^D]$ and D is the fractal dimension.

Since (by hypothesis) equation (3) approximates equation (2), comparison of equations (3) and (1) lead to the conclusion that y_i^* is a fractal set, thus a fractal specific capacity. Such a capacity exhibits fractal statistical properties.

CONCLUSIONS

The tendency of discharge rate decay that is observed in most single well pumping tests, in fractured rocks even for production tests of short duration seems to be consistent with the idea of a hydraulic conductor of finite volume reservoir. As long as the hydraulic conductor is assumed to be a random sample of the regional fractured aquifer then it is possible to define a fractal specific capacity for which the well discharge is constant.

As far as parameter evaluation in fractured rocks is concerned, Boulton and Streltsova method was used for estimates with the fractal specific capacity. Results are in agreement with values found in the literature for igneous and metamorphic rocks.

REFERENCES

Bear J (1972) Dynamics of Fluids in Porous Media. New York, Elsevier

Boulton NS, Streltsova TD (1977) Unsteady flow to a pumped well in a fissured water-bearing formation. J Hydrol 35:257-269

Gustafson G, Krásny J (1994) Crystalline rock aquifers: their occurrence, use and importance. Applied Hydrogeology 2(2):64-75

Guerin FPM, Billaux DM (1993) On the relationship between connectivity and the continuum approximation in fracture flow and transport modeling. In: CONG INT ASS HYDROGEOL, 24 Oslo, 1993. Memoires Oslo, IAH, p 215-224

Himmelsbach T, Hotzl H, Maloszewski P (1994) Forced gradient tracer tests in a highly permeable fault zone. Applied hydrogeology 2(3):40-47

Peitgen HO, Jurgens H, Saupe D (1992) Fractals for the classroom. Part one: introduction to fractals and chaos. New York,Springer Verlag, 452 p

Snow DT (1968) Rock frature spacing, openings and porosities. J Soil Mech Found Div, Proc Am Soc Civ Eng 94(1): 73-91

Turcotte DL (1992) Fractals and chaos in geology and geophysics. Cambridge University Press. 221p

A tracer based flow-log technique to assess hydraulic properties in deep fractured-porous aquifers of low permeability applied in the 4000 m pilot borehole of the KTB, Germany

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A b s t r a c t : A tracer based flow-log technique suitable for very low flow velocities (down to $5 \cdot 10^{-5}$ m/s in the drilling) which surpass the sensitivity of conventional flowmeters has been developed and tested in the pilot borehole of the KTB / Germany (KTB-VB). The movement of a pronounced salinity gradient is monitored during a non steady-state low pressure injection using resistivity measurements. This enables the identification of discrete fractures as well as zones of porous permeability and a quantification of their hydraulic properties. The results were verified qualitatively by an independent fluid logging test. The experimental technique and the data processing including depth correction, flow rate determination and derivation of a permeability profile are described. Furthermore, the findings for the open hole of the KTB-VB (3850 – 4000 m) which penetrates the Franconian lineament, an important fault zone of the continental crystalline crust, are presented.

EXPERIMENTAL CONCEPT

Conventional flow-log techniques using impeller or spinner flowmeters require high flow rates (typically 100 L/min; Molz *et al.* 1989; Keys and Sullivan 1979) which are difficult to be realized in deep aquifers of low transmissivity. Even modern high resolution heat-pulse or electromagnetic flowmeters require more than 0.1 L/min (Paillet *et al.* 1996) and are difficult to employ in the high pressure high temperature environment of deep drillings. For the rather common situation of a pronounced salinity gradient in a borehole, resistivity measurements during a slow injection process offer an efficient alternative. This combines the advantages of low technical expense and neglectable disturbance of the investigated aquifer.

A slow injection process (4.8 m^3 in 7 d) was carried out by simply filling up the borehole maintaining a permanent overflow condition. This provides a well defined upper boundary condition. The injection rate $Q_{tot}(t)$ was measured pointwise by monitoring the water level subsidence during short interruptions of the water supply. During the injection the freshwater to saltwater transition was pushed downwards. This was monitored with a mud-resistivity-pressure logging tool (MRP-tool). The MRP-tool was moved down in steps of several meters, separated by standstill phases of several hours in a way that it was always located close to the steepest part of the salinity gradient. As the injection lasted several days it had to be interrupted overnight when no cable operation was possible. This results in a highly non steady-state process.

Within a sequence of stepdown and standstill phases, the same salinity is measured repeatedly at different times and depths (fig.1). When the cross sectional area A of the drilling is known, the flow rate Q can be calculated from the vertical and temporal distances (Δz and Δt) between two subsequent recordings of the same salinity value. The accuracy of flow rate determination can be improved by calculating $\Delta V = A \cdot \Delta z$ and Δt for any salinity value available within a standstill phase. Thus, the flow rate is given as slope of the $\Delta V(\Delta t)$-relationship.

DEPTH CORRECTION

Since flow rate calculation is based on depth differences a high differential accuracy of depth data is required. A twisted borehole trajectory causes intense cable friction resulting in a delay of MRP-tool movement relative to cable movement (measured at surface) when cable movement starts or stops. The resulting differential errors in the depth raw data have to be eliminated to avoid severe errors of calculated flow rates. Because a stepdown covers only a few meters, gamma-log is not sufficient to solve this problem. Therefore, the integration of a high resolution pressure sensor in the MRP-tool is essential. As the upper boundary condition is known exactly, depth correction can be performed using these pressure measurements. During cable movement the pressure records show strong oscillations probably induced by cable friction. These strong oscillations have to be eliminated first by fitting smooth functions to enable depth correction.

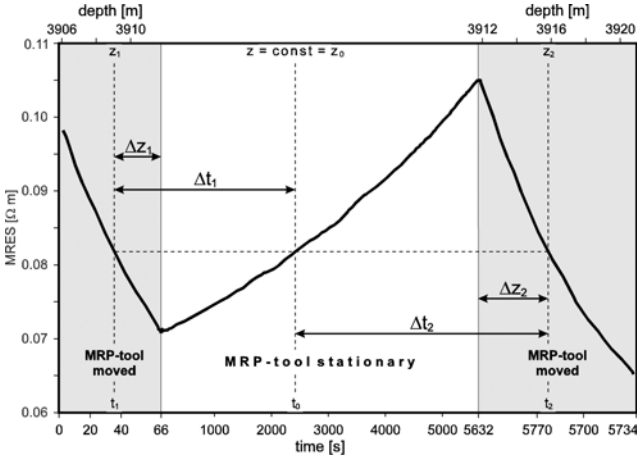

Figure 1. Analysis of MRP-stepdown data for one MRES-value

DERIVATION OF A PERMEABILITY PROFILE

Whereas the flow rate $Q_{tot}(t)$ measured at surface is equivalent to the injection rate for the complete open hole section, the flow rate Q(z,t) at MRP-tool position z characterizes the injection rate below this depth. As expected, Q(z,t) equals $Q_{tot}(t)$ at the depth of the casing shoe and falls below it for greater depth.

The derivation of permeability profiles from flow-log data registered under quasi steady-state conditions is described in detail by Paillet (1998) for fractured aquifers. The non steady-state characteristic of this test requires a permeability model including one more simplification. The same characteristic b(t) of transient behavior of the injection process has to be assumed for any depth, thus the vertical flow rate in the well at depth z is given by

$$Q(z,t) = b(t) \int_{z_{bot}}^{z} K(zz) \left(p(zz,t) - p_{eq}(zz) \right) dzz$$

where z_{bot} = bottom of drilling
K(z) = permeability at depth z (a fracture with transmissivity T_f at depth z_f would be represented by $\delta(z-z_f) \cdot T_f$)
$\delta(.)$ = delta function (Dirac distribution)
p(z,t) = actual fluid pressure in the well

$p_{eq}(z)$ = initial equilibrium pressure in the formation

The characteristic of transient behavior gets eliminated from the ratio $R(z,t) = Q(z,t) / Q_{tot}(t)$:

$$R(z,t) = \frac{Q(z,t)}{Q_{tot}(t)} = \frac{\int_{z_{bot}}^{z} K(zz)\left(p(zz,t) - p_{eq}(zz)\right)dzz}{\int_{z_{bot}}^{z_{top}} K(zz)\left(p(zz,t) - p_{eq}(zz)\right)dzz}$$

where z_{top} = position of the casing shoe

$p_{eq}(z)$ is known from a pressure-log preceding the injection test and p(z,t) can be derived from the actual pressure record. Therefore, the parameters of a permeability model K(z) can be determined by fitting the observed R(z,t)-data, except for a constant factor. A reasonable choice for this factor is the total transmissivity T_{tot} of the open hole section. This should be determined more reliably by an independent hydraulic test involving larger injection or extraction volumes.

The pressure p(z,t) needed to calculate R(z,t) is measured only at MRP-tool position at a given time. For any other depth it has to be calculated using the hydrostatic pressure gradient. For the initial situation when the open hole section is filled with formation fluid, the difference $p(z,t) - p_{eq}(z)$ is independent of depth. Later on, this is still true below the saltwater to freshwater transition. Above this transition the vertical pressure gradient in the well is less steep than in the formation due to the lower density of the fresh water. This results in an increase of $p(z,t) - p_{eq}(z)$ from the saltwater to freshwater transition towards the casing shoe. Because the applied injection pressure is low (0.05 to 0.15 MPa) this effect which is usually neglected in flow-log interpretation is relevant, although the density differences are small (approx. 4 %, summing up to 0.06 MPa for an open hole section of 150 m).

PERMEABILITY PROFILE OF THE KTB-VB OPEN HOLE SECTION (3850 – 4000 m)

A small volume drawdown test was carried out subsequent to the injection test to detect hydraulically relevant fractures. Highly saline formation fluid drawn from fractures would cause salinity plumes in the borehole, which is filled with a low salinity fluid at that time. Lower boundaries of salinity plumes mark fracture positions. A relevant fracture was found at 3946.5 m (fig.2). The rise of saline fluid from the bottom indicates another relevant hydraulic pathway below 3980 m (max. logging depth).

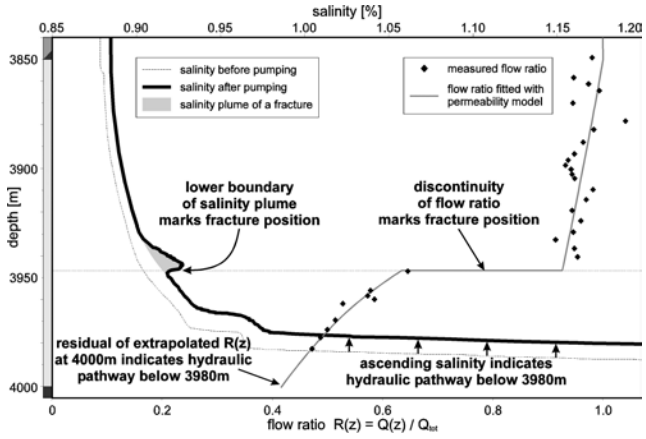

Figure 2. Comparison of results from fluid logging and flow-log

A significant jump in the R(z,t)-data between 3940 m and 3947 m offers an independent affirmation of the detected fracture (fig.2). Furthermore, the extrapolation of the R(z,t)-data results in values clearly greater than 0 at the bottom of the borehole, thus validating the assumption of another fracture below 3980m. Therefore, a model was fitted to the measured data, including fractures at 3946.5 m and 4000 m (indications for these fractures can also be found in loggings of various chemical and geophysical parameters reported by Heinschild *et al.* 1990 and Rauen *et al.* 1990) and assuming sections of constant permeability between the fractures (fig.3). The two fractures contribute approx. 75 % to the total transmissivity.

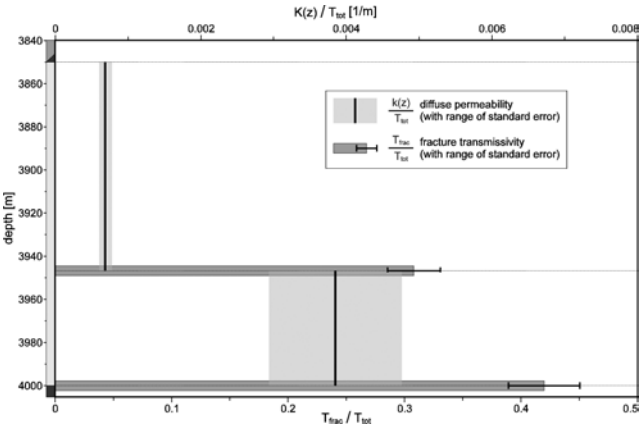

Figure 3. The permeability model fitted to KTB-VB flow-log data

CONCLUSIONS

In case a pronounced salinity gradient exists in a borehole, the flow-log technique presented here facilitates the measurement of flow velocities as low as $5 \cdot 10^{-5}$ m/s with a moderate technical expense. The required effort for data processing is relatively high but can be automatised for the most part. Assuming some reasonable simplifications the method enables the derivation of a permeability profile. The results show good agreement with other independent measurements.

ACKNOWLEDGEMENTS

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REFERENCES

Heinschild KJ, Stroh A, Tapfer M, Wittenbecher M (1990) Geochemie. In Emmermann R, Dietrich HG, Lauterjung J, Wöhrl T (eds) Tiefbohrung KTB-Oberpfalz VB, Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor – Teufenbereich von 3500 bis 4000.1 m. KTB Report 90-2:C1-C65

Keys WS, Sullivan JK (1979) Role of borehole geophysics in defining the physical characteristics of the Raft River geothermal reservoir, Idaho. Geophysics 44:1116-1141

Molz FJ, Morin RH, Hess AE, Melville JC, Guven O (1989) The impeller meter for measuring aquifer permeability variations – evaluation and comparison with other tests. Water Resour Res 25(7):1677-1683

Paillet FL (1998) Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations. Water Resour Res 34(5):997-1010

Paillet, FL, Crowder RE, Hess AE (1996) High-resolution flowmeter logging applications with the heat-pulse flowmeter. J Environ Eng Geophys 1:1-14

Rauen A, Huenges E, Bücker C, Wolter KE, Wienand J (1990) Geophysik. In Emmermann R, Dietrich HG, Lauterjung J, Wöhrl T (eds) Tiefbohrung KTB-Oberpfalz VB, Ergebnisse der geowissenschaftlichen Bohrungsbearbeitung im KTB-Feldlabor – Teufenbereich von 3500 bis 4000.1 m. KTB Report 90-2:D1-D64

Radially convergent tracer test in the Chalk

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A b s t r a c t : For sustainable groundwater management and protection issues it is necessary to determine flow and transport properties, which can be investigated in-situ using tracer tests. A forced gradient tracer test was conducted on the Chalk aquifer in north-east England, where it is confined by glacial deposits. The upper 50 m of confined Chalk were subjected to radially convergent flow conditions (by pumping a well) and tracers were introduced in injection boreholes. The results suggest that cross-bedding flow exists despite the presence of marl layers, and probably occurs along persistent joints or faults. The shape of the breakthrough curves indicates non-Fickian behaviour, probably caused by diffusion of solute between the matrix and fractures. Borehole dilution test data and observations from the Chalk in quarry exposures are also reported.

INTRODUCTION

The chalk aquifer is the most important aquifer in the United Kingdom, providing more than 50 % of the abstracted groundwater. The Chalk is a dual porosity aquifer with a high matrix porosity of approximately 35 % in the northern chalk province of England (Allen *et al.* 1997). Due to the small pore diameter of 0.1 to 1.0 μm the matrix has a very low hydraulic conductivity (permeability) of about 10^{-4} m/d (Price *et al.* 1993). The bulk permeability is enormously increased by fractures and faults, the latter extending over several beds. Marl (clay rich) bands along bedding planes may act to restrict vertical flow.

AIMS

To investigate the transport characteristics of the aquifer including solute velocities, horizontal and vertical communication, mechanical dispersivities, extent of diffusion into the matrix, effective porosity and fracture apertures a forced gradient, radially converging tracer test has been conducted.

TEST SITE

The tracer test site is situated in northern England (grid reference TA 062 472) and confined by a ca. 11 m thick overlying drift layer. Three ca. 72 m deep injection wells are situated 25 m from an 80 m deep abstraction borehole with a further injection well

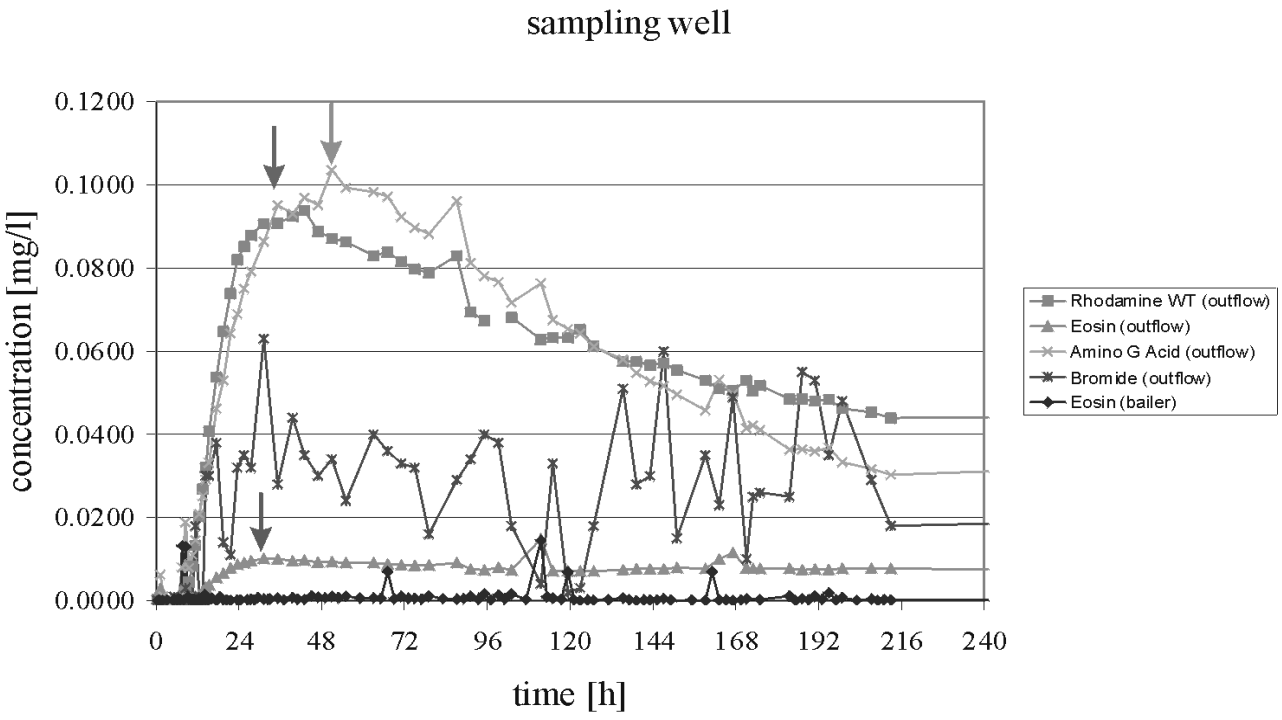

Figure 1. Breakthrough curve from the lower (outflow) and upper (bailer) sampling level of the abstraction well. Arrows indicate the max. concentration. Eosin peaks 31 hours after the start of the test, followed by Rhodamine WT (37 h) and Amino G Acid (51 h)

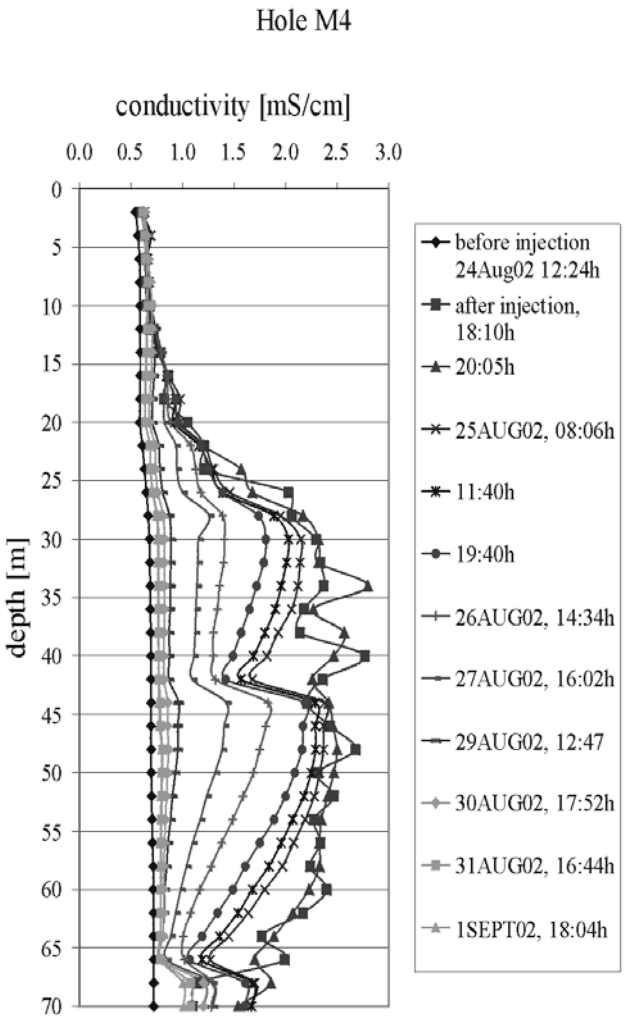

Figure 2. Dilution profile from the 75 m borehole. Flowing horizons can be identified at 42 and 66 m depth

75 m away. Hydraulic packer tests and geophysical logging have shown the presence of two highly permeable horizons above 44 m and between 67 and 69 m depth.

Observations from quarry exposures near the tracer test site indicate that the Chalk consists of some massive beds, up to 1 m thick, with widely spaced joints, and thinner beds which are more closely jointed. It contains laterally extensive clay layers (marls) up to 2 cm thick, which occur at 0.5 to 2 m intervals. It is also cut by normal faults with lengths of 20 m or greater, and throws of up to 0.5 m, which often contain brecciated chalk up to 10 cm thick. The marl layers are expected to act as barriers to deep saline water whereas the joints and normal faults may act as conduits.

METHODS

Tracers were injected into the wells 25 and 75 m away from the pumped well after a steady state flow field was reached by pumping at 330 m^3/d. One injection well was packered into upper (Eosin and potassium bromide) and lower (Sodiumfluorescein and sodium iodide) sections to test the two permeable horizons separately. Accordingly the abstraction well was sampled at two depths using the outflow of the pump (which gave the average of all the inflow) and a bailer (at 50 m depth, which sampled only waters entering above this depth). Tracers in two other injection wells consisted of Amino G Acid plus potassium chloride, and Rhodamine WT. These injection wells were recirculated and sampled to determine the source function. Sodium chloride was injected into the furthest injection well (which was not circulated) and borehole dilution was monitored at 2 m depth intervals using a conductivity meter.

RESULTS

The breakthrough curves from the abstraction well (fig.1) show that the concentrations from the lower sampling level (pump outlet) are much higher than in the upper level (bailer) indicating greater solute flux entering the lower part of the abstraction well from the other boreholes. Eosin, which was injected in the upper half of the packered well, is on average 20 times less concentrated in the upper sampling level than in the lower one, thus proving the presence of vertical flow in the aquifer.

In the outflow data Eosin and Rhodamine WT peak first, at ca. 31 and 37 hours respectively, followed by Amino G Acid at around 51 h. The high concentrations of Rhodamine WT and Amino G Acid indicate a good connection with the pumped well, while Sodiumfluorescein was not detected.

The borehole dilution test results (fig.2) indicate that flow occurred pervasively through the formation, but was focussed in two fractured horizons at 42 and 66 m depth. Comparison with core and acoustic logs indicates that these levels correspond to fractured horizons just above marl layers. The results suggest that these marls represent barriers to vertical flow, and the injection well breached these barriers, resulting in vertical flow in the well. An interpretation of the borehole dilution data incorporating vertical flow in the well is proposed and its validity is investigated by comparison with packer test data.

REFERENCES

Allen DJ, Brewerton LJ, Coleby LM, Gibbs BR, Lewis MA, MacDonald AM, Wagstoff SJ, Williams AT (1997). The physical properties of major aquifers in England and Wales; British Geological Survey, Technical Report WD/97/34.312p Environment Agency, R&D Publication 8

Price M, Downing RA, Edmunds WM (1993: The chalk as an aquifer. In: Downing RA, Price M, Jones GP (eds) The hydrogeology of the Chalk of north-west Europe; Oxford Science Publications

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Investigation of matrix diffusion in deep hot-dry-rock reservoirs using single-well injection-withdrawal tracer tests

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A b s t r a c t : Matrix diffusion of tracers in porous media is depending on both rock and tracer properties. The effect of matrix diffusion on tracer transport is however often masked by hydrodynamic dispersion. The ambiguity of tracer test results can be reduced when two or more conservative tracers with different diffusion coefficients are applied. An approach using a single-well injection-withdrawal test and first results from design calculations are presented.

INTRODUCTION

The dimensioning of geothermal energy usage from deep hot-dry-rock reservoirs requires knowledge of the effective heat exchange surface between liquid and solid phases. Tracer tests are an appropriate technique for the investigation of this surface since matrix diffusion and hence tracer transport is a function of the effective contact area. However, investigations within such reservoirs are difficult: Usually only one borehole is available due to economic restrictions, high temperature stimulates tracer decay, and matrix diffusion is masked by hydrodynamic dispersion within the advective pore space due to heterogeneity.

To overcome these difficulties, an experimental concept was developed. It is based upon the synchronous application of several non-retarding tracers with different diffusion coefficients. Using the single-well injection-withdrawal (SWIW) technique (Meigs and Beauheim 2001), the effect of hydrodynamic dispersion is partially reversed, while the effect of molecular matrix diffusion is enhanced (Tsang 1995). Hence the differences between the tracer breakthrough curves are mainly due to different matrix diffusion. Knowing the diffusion coefficients of the individual tracers, an effective contact surface between liquid and solid phases can be estimated. Since each tracer is subjected to the same advection and dispersion, the formation heterogeneity is of minor importance and the different transport behaviour can be attributed to the molecular diffusion only.

MATERIALS AND METHODS

Tracers

The tracers under investigation are sulfonated naphthalene-formaldehyde condensates (SNFC) and the corresponding monomeres. These compounds are available in various chain lengths, spanning a range of aqueous diffusion coefficients. Modern HPLC methods enable their analysis down to a µg/L level (Piottea *et al.* 1995, Wolf *et al.* 2000). Since SNFC are environmentally benign, they could be recently applied within the unsaturated soil zone (Nimmo *et al.* 2002), in a shallow aquifer as multi-tracer mixture (Menzel *et al.* 2002), and in geothermal systems (Rose *et al.* 2001).

Laboratory experiments

The laboratory diffusion experiments will be conducted in accordance to a technique, initially presented by (Skagius and Neretnieks 1986). Fig.1 presents the experimental setup. The rock sample (1) is saturated with formation water and covered with epoxy resin so that only one face remains accessible. The sample is set into a PVC support frame (3) with the open face connected to a water reservoir (2) containing formation water. At the beginning of the experiment, the two tracers, only differing with respect to their diffusion coefficients (e.g. fluorescein, 2-naphthalene-sulfonate) are added ($C=C_0$). The concentration of the tracer solution decreases with time ($t_0<t<t_1$) because of tracer diffusion into the rock material. After the diffusion phase the tracer solution is replaced by tracer free formation water ($C=0$) at $t=t_1$ and the increase in concentration is observed in the reservoir chamber. In order to mimic the exchange of water in the fracture during a field experiment and to uphold the concentration gradient ($t_1...t_n$) for higher tracer flux, the reservoir water is exchanged against tracer free formation water ($C=0$) at regular intervals (fig.2). The dimensioning of the experiment (tracer concentrations, contact surfaces, volume of water reservoir, durations etc.) is carried out based on the given parameters of the rock material so that a transfer to actual field conditions is possible. In order to avoid the influence of a change in temperature on the diffusion process, the experiment is conducted at constant temperature.

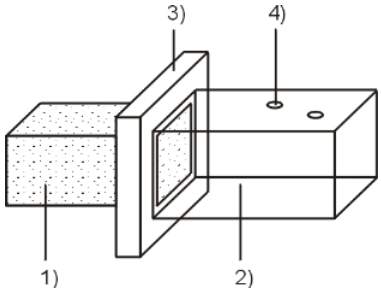

Figure 1. Diffusion cell with (1) resin coated rock sample, (2) water reservoir, (3) support frame, (4) access holes for exchange of water/tracer, modified after (Skagius and Neretnieks 1986)

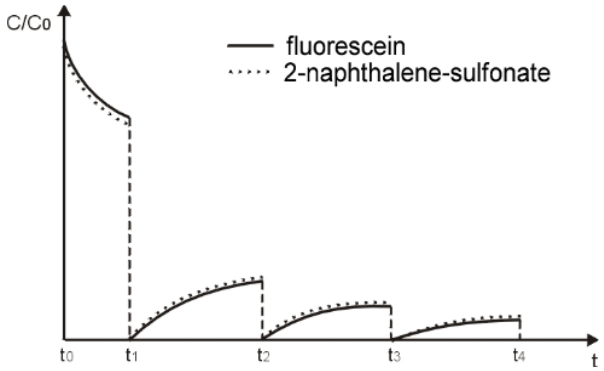

Figure 2. Schematic temporal change in concentration of the two tracers in the reservoir. t_0 beginning of tracer experiment, $t_1 \ldots t_n$ exchange of formation water in the reservoir

Field experiments

Pilot field experiments are carried out at boreholes with a priori well known fracture structures. A fracture zone is isolated with a double-packer string and water, together with two or more tracers and an additional slug of water (chaser) injected into the fracture (fig.3). The volume of the chaser mainly depends on the volume of the packer tubing string. The injection rate should correspond ideally to the abstraction rate.

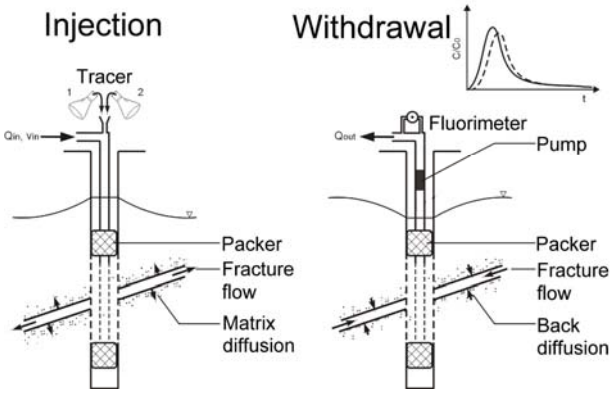

Figure 3. Schematic of the experimental setup for the pilot field experiments

The injection phase is followed by a rest period without injection or abstraction. During this period the two tracers will diffuse with different rates into the fracture adjacent rock matrix. The length of the rest period will be based, among other parameters, on the results of the laboratory experiments. Depending on the specific field site, it has to be assumed that there is no significant "background" groundwater flow. Otherwise advanced numerical models have to be employed to interpret the tests, which adds another dimension of complexity and increases ambiguity.

The rest period is followed by the production phase during which the back diffusion of the tracers is active. Apart from the maxima of the breakthrough curves, the tailing part of the breakthrough curve is of particular importance for the interpretation of the test because it contains the information on the differential back diffusion process. For the interpretation of the tracer tests analytical models as well as numerical models will be employed, depending on the boundary conditions. Mathematical models exist (e.g. Maloszewski and Zuber 1990) that can also take into account sorption effects of the tracers.

FIRST RESULTS

To design the laboratory experiments, the period of diffusive tracer uptake by the rock sample ($t_0 \ldots t_1$) was calculated using a short-term approximation of the analytical solution of the advection-dispersion-equation (Barrer 1978), which can be expressed in terms of tracer concentration in the reservoir as:

$$\frac{C}{C_0} = 1 - 2\frac{A}{V}\left(\frac{f}{1-f}\right)\sqrt{\frac{D_a t}{\pi}}, \qquad (1)$$

where A/V (m^{-1}), f (-) and D_a ($m^2 s^{-1}$) denote the surface to volume ratio, the fractional tracer uptake at equilibrium, and the apparent diffusion coefficient. According to experimental setup, a surface to volume ration of 0.1 m^{-1} and a fractional uptake of 0.9 was used. The apparent diffusion coefficients were calculated for 20°C after (Grathwohl 1998) and (Worch 1993).

The different molecular sizes of fluorescein and 2-naphthalene-sulfonate cause a measurable difference of the concentration time series (fig.4).

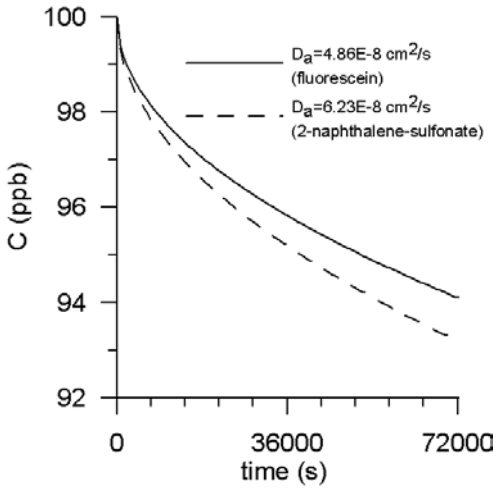

Figure 4. Calculated time series of tracer concentration in a batch experiment

REFERENCES

Barrer RM (1978) Zeolites and clay minerals as sorbents and molecular sieves. Academic Press, London, 497 pp

Grathwohl P (1998) Diffusion in Natural Porous Media: Contaminant Transport, Sorption / Desorption and Dissolution Kinetics, Boston, 228 pp

Maloszewski P, Zuber A (1990) Mathematical modeling of tracer behavior in short-term experiments in fissured rocks. Water Resources Research 26(7):1517-1528

Meigs LC, Beauheim RL (2001) Tracer tests in fractured dolomite 1. Experimental design and observed tracer recoveries. Water Resources Research 37(5):1113-1128

Menzel CM, Lange FT, Käss W, Hötzl H (2002) Occurrence of naphthalenesulfonates and their condensates with formaldehyde in a landfill leachate and their transport behavior in groundwater of the Upper Rhine Valley, Germany. Environmental Geology 41(6):731-741

Nimmo JR, Perkinsa KS, Rose PE, Rousseauc JP, Orrc BR, BV T, Andersonc SR (2002) Kilometer-Scale Rapid Transport of Naphthalene Sulfonate Tracer in the Unsaturated Zone at the Idaho National Engineering and Environmental Laboratory. Vadose Zone Journal 1:89-101

Piottea M, Bossányia F, Perreaulta F, Jolicoeur C (1995) Characterization of poly(naphthalenesulfonate) salts by ion-pair chromatography and ultrafiltration. Journal of Chromatography A 704,2:377-385

Rose PE, Benoit WR, Kilbourn PM (2001) The application of the polyaromatic sulfonates as tracers in geothermal reservoirs. Geothermics 30(6):617-640

Skagius K, Neretnieks I (1986) Porosities and diffusivities of some nonsorbing species in crystalline rocks. Water Resources Research 22(3):389-398

Tsang YW (1995) Study of alternative tracer tests in characterizing transport in fractured rocks. Geophysical Research Letters 22(11):1421-1424

Wolf C, Storm T, Lange FT, Reemtsma T, Brauch H-J, Eberle SH, Jekel M (2000) Analysis of Sulfonated Naphthalene-Formaldehyde Condensates by Ion-Pair Chromatography and Their Quantitative Determination from Aqueous Environmental Samples. Analytical Chemistry 72(21):5466 –5472

Worch E (1993) Eine neue Gleichung zur Berechnung von Diffusionskoeffizienten gelöster Stoffe. Vom Wasser 81:289-297

Hydrogeologic maps in hardrock environment: what should they represent?

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Abstract: Fractured igneous, metamorphic and consolidated sedimentary rocks (so called hard rocks) occur in extended regions all over the world. In recent years, mainly due to important practical groundwater issues connected with this specific hydrogeologic environment, increasing interest in hardrock hydrogeology has been noted. Still, in many hydrogeologic maps "hardrock" areas are represented either without aquifers (or of a small to negligible groundwater potential) or are left blank at all. It is evident that generally accepted methodology of hydrogeologic map compilation can be only partly applied in hardrock environments because of their specific hydrogeologic features. Some suggestions how to come to terms with this issue are presented in this paper.

INTRODUCTION

In terms of hydrogeology, extended areas with outcropping hard rocks differ considerably from hydrogeologic basins. Due to many practical reasons, especially usual suitability for concentrated groundwater abstraction, the latter have been, in contrast to hardrock areas, subject of intensive hydrogeologic studies since long ago. Therefore, during past decades no adequate attention had been paid to hardrock environments, except for some arid and semi-arid regions where groundwater has been the only source for water supply. Recently, increasing interest in hardrock hydrogeology has been noted also in temperate climatic zones due to its groundwater importance in many applied tasks. It is evident that recommended general methodologies of hydrogeologic map compilation (e.g. Anon 1970, 1977, 1980, Struckmeier, Margat 1995) can hardly be applied in the specific hardrock environment without any modification.

PRESENT STATE

In many previous hydrogeologic maps hardrock areas have been represented either without aquifers (or of small to negligible groundwater potential) or are left blank at all. Yet, it is clear, that some recommendations should be given how to represent specific features of these environments to advance in hydrogeologic mapping and in hydrogeologic understanding of these areas. This would offer a reasonable basis both for theoretical hydrogeologic considerations and for practical decisions. Unfortunately, only a few attempts have been made to cope with this issue (comp. e.g. Grimmelmann et al 1983, Struckmeier et al 1989).

SUGGESTIONS

Two main points of view determine the scope and content of hydrogeologic maps: their scale and their objectives.

As to the scale large-, medium- and small-scale maps are commonly distinguished, with the limits at approximately 1:100,000 and 1:1,000,000 scales, resp. (Struckmeier, Margat 1995). The same authors distinguish also two main groups of maps, corresponding with their aims: general hydrogeologic maps on one hand and parameter maps and special purpose maps on the other. The practical purpose of the latter maps mostly determines their content and appearance. Regarding the general maps long-term experience of hydrogeologic map compilation tells that all the versatile hydrogeologic reality cannot be merged in one sheet of paper or one resulting product of a GIS-supported map.

Possible division of content of hydrogeologic maps after distinct aspects (two quantitative and one qualitative) is represented in Table 1.

Considering the scale, small scale maps, representing continents or extended areas as e.g. the Hydrogeological map of Europe in 1:1,500,000 mostly distinguish distinct types of hydrogeologic environment. On the other hand, the large-scale maps are mostly based on and represent results of detailed hydrogeologic studies focused on specific, usually applied problems.

The medium scale maps often form sets of sheets that cover extended territories. They are between small-scale maps that provide a basis to scientific considerations and large scale maps where also exact information, applicable for concrete activities, is requested. This is mostly the point that makes difficult the compilation of these hydrogeologic maps in general and in a very complex and variable hardrock environment specifically. The main problem is how to reflect in a local scale very variable point information and how to extend it to be represented in a map.

As groundwater quality is usually not very variable these maps used to be compiled without problems. So it is also as to natural groundwater resources representation in temperate climatic zones where commonly used methodology is based on groundwater runoff assessment from total runoff in water courses. More complicated situation is in arid regions but equalising effect of climatic conditions often makes possible using of point data even to draw regional estimations.

The most complicated is representation of hydraulic parameters. Transmissivity is generally considered the best one, both due to its most frequent availability and its suitability to express groundwater abstraction possibilities in the first approximation. A suggested quantitative approach is based on statistical treatment of available transmissivity data and the objective classification of transmissivity magnitude and variation (Krásný 1993). Extension of the mapped area and the size of hydrogeologic inhomogeneity elements and character of overburden and juxtaposed Quaternary deposits is to be taken into account in hardrock areas, too (Krásný 2002). Superposed over a transmissivity background, mostly derived from results of aquifer tests carried out in water wells, important spatial, linear or point heterogeneities (anomalies) are represented. Compiled hydrogeologic maps (Krásný, López 1989, Darko, Krásný 2003) indicate suitability of using such an approach even in extended areas.

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REFERENCES

Darko PK, Krásný J (2003) Regional transmissivity distribution and groundwater potential of hydrogeological units in Ghana. Ext.Abstract in this Volume.

Grimmelmann WF, Krampe KDW, Struckmeier WF (eds) (1983) Hydrogeological mapping in Asia and the Pacific region. Proc. ESCAP-RMRDC Workshop Bandung. IAH Internat.Contribution to Hydrogeol. 7. 410 pp.

Krásný J (1993) Classification of transmissivity magnitude and variation. Ground Water 31,2,230-236.

Krásný J. (2002): Quantitative hardrock hydrogeology in a regional scale. – Bull. of Geol. Surv. of Norway (NGU-Bull) 439, 7-14. Trondheim.

Krásný J, López A (1989) The general hydrogeological map of Nicaragua 1 : 250 000: principles of compilation and content. - Mem. Internat. Sympos.on Hydrogeological maps as tools for economic and social development:413-422. Hannover.

Struckmeier WF, Grimmelmann WF, Krampe KDW (eds) (1989) Mem.Internat.Sympos. on Hydrogeological maps as tools for economic and social development. Hannover. 598 pp.

Struckmeier WF, Margat J (1995) Hydrogeological maps. A guide and a standard legend. IAH Internat.Contribution to Hydrogeol. 17. 177 pp.

Anon (1970) International legend for hydrogeological maps. UNESCO-IASH. 102 pp.

Anon (1977) Hydrological maps. A contribution to the International Hydrological Decade. UNESCO-WMO. 204 pp.

Anon (1983) International legend for hydrogeological maps. Revised version. IAH-IAHS-UNESCO. 51 pp.

Anon (1963-present) Different sheets of the Hydrogeological Map of Europe in 1:1,500,000.

Table 1. Hydrogeologic elements, properties and phenomena to be represented in hydrogeologic maps

<table>
<tr><td>→ ASPECTS</td><td colspan="3">QUANTITATIVE
(GROUNDWATER “POTENTIAL“)</td><td>QUALITATIVE</td><td rowspan="2">CARTOGRAPHIC
MEANS</td></tr>
<tr><td>→ MAP OF
↓ TYPE OF INFORMATION</td><td>GW ABSTRACTION POSSIBILITIES</td><td colspan="2">NATURAL (INDUCED, ARTIFICIAL) RESOURCES</td><td>GW QUALITY</td></tr>
<tr><td>BACKGROUND *)</td><td colspan="4">HYDROGEOLOGIC ENVIRONMENT
(geometry and anatomy of hg bodies, position of inhomogeneities
HYDROGEOLOGIC BOUNDARIES
(chosen after the aim of the map - e.g. limits of aquifers or aquifer systems)</td><td>ORNAMENTS,
LINES</td></tr>
<tr><td rowspan="2">PRINCIPAL **)</td><td>transmissivity [m^2/d]
specific capacity q[L/s m]
transmissivity index Y [log 10^6q]</td><td colspan="2">recharge [mm]
GW throughflow [L/s, m^3/s]
GW runoff (discharge) [L/s km^2]
storage [dimensionless]
GW volume [m^3]</td><td>basic chemical types
TDS
minor constituents
salinity
pollution</td><td>COLOURS
ORNAMENTS
LINES</td></tr>
<tr><td colspan="4">after consideration, e.g.: equipotential (and flow) lines
important HG boundaries</td><td>LINES</td></tr>
<tr><td>ADDITIONAL ***)</td><td colspan="4">selected or reduced information not represented as principal info, e.g.:
thickness of aquifers (aquitards), depth to groundwater level
boundaries between geologic or hydrogeologic units, GW divides
areas affected by different human activities
sources of point or diffuse gw contamination (potential of real)
protection zones
water wells, springs, climatic or gauging stations</td><td>ORNAMENTS
(CONTOUR) LINES
POINTS</td></tr>
</table>

*) information derived mainly from geologic, hydrologic, climatic and other data
**) information selected according to the aim of the map
***) information completing hydrogeologic image of the represented area

GW = groundwater, HG = hydrogeologic

Multi-parameter geophysics: an essential tool to delineate aquifers in fractured rocks

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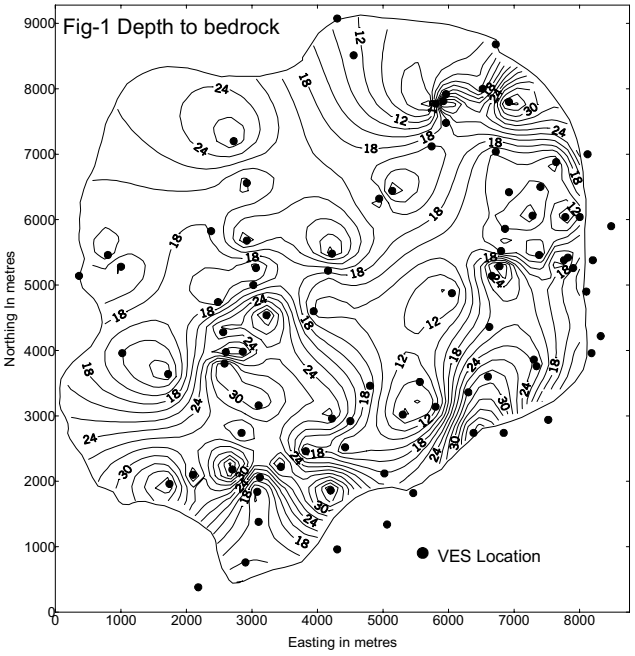

Figure 1. Depth to bedrock

The study of groundwater in hard fractured rocks is a challenging task due to large heterogeneity and complexities of the crystalline rocks. These rocks exhibit anisotropic behavior and thus there exist an irregular distribution of groundwater. The flow in this type of system is mainly governed by the distribution and extent of fracturing in the primary rocks, their orientation, density and connectivity. Delineation of fracture system through surface or subsurface geophysics is important for water resources development in such areas.

In the present study, the groundwater status and resources were investigated in a typical fractured rock system using the integrated geophysical approach comprising of both surface and sub-surface geophysical methods. An attempt is made to identify the fractured zone in the granitic terrain through a number of geophysical techniques. Geophysical resistivity survey using Schlumberger configuration was carried out at 86 sites in a small watershed of 60 Sq Km around Maheshwaram, Andhra Pradesh, India. The study area lies between latitude $17^0$06'20"N to $17^0$11'00"N and longitude $78^0$24'30"E to $78^0$29'00"E. These electrical resistivity soundings provide information on top layer thickness and resistivity, weathered layer thickness, weathered/fractured layer resistivity and thickness and depth to basement. The depth to basement contour map provided us better insight over the possible bottom of the aquifer through out the watershed. The depth to basement varied from 4m to about 40m bgl and is shown in Fig.1.

Based on interpretation, 25 sites were drilled which encountered fractures of various density and at different depths Krishnamurthy *et al.* (2000). Mise-à-la-masse technique was applied in the study area at 5 sites near the drilled wells and was able to delineate the lateral extension of fractures based on equipotential trend Kumar *et al.* (2003). The idea is to use a subsurface conductive mass (in this case water bearing fracture) as energization point. The SP studies carried out near these borewells have also shown extension of fractures at some of the sites. The equipotential contour maps drawn from mise-à-la-masse and surface SP studies at borewell no. 265 is shown in Fig.2. Two borewells drilled at two sites based on the anomalies in mise-à-la-masse and SP maps have encountered fracture nearly at the same depths as in the main well (BW-1 and BW-2 in fig.2). Another borewell drilled at a different site (BW-3 in fig.2) has not encountered fractures, but of course the experiment could not be done upto that site because of lack of space. Borehole geophysical logging with Point Resistance, Long and Short Normal, Gamma log, Self-Potential and Temperature logs were carried out at 9 wells, fairly distributed in the watershed to identify the minor fractures that otherwise are missed during VES interpretation. The Point Resistance, Long and Short Normal logs have shown low resistivities against the fracture zones.

In some borewells, the gamma log has shown high activity against the fracture zone. This may be due to the accumulation of clay content in such places. The logging studies have helped in knowing the different zones of fractures at different depths,

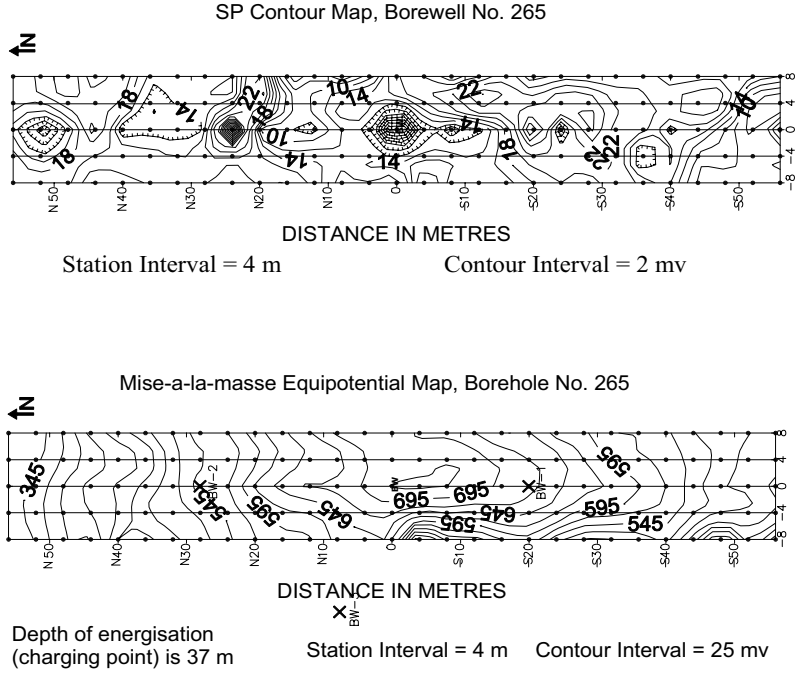

Figure 2. Equipotential map

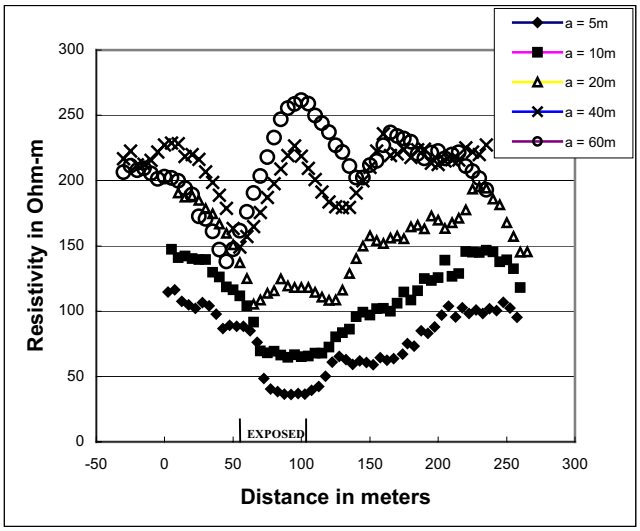

Figure 3. Two-Electrode Resistivity Profiles Over a Dyke

which corroborates well with the geological lithologs. The resistivity sounding, Mise-à-la-masse, SP and well-logging interpretation give significant correlation for the aquifer's weathered and fractured zones. The resistivity profiling with two-electrode (pole-pole) configuration, carried out across dykes (Fig.3) has indicated that the dykes are acting as conduits at shallow depths and acting as barriers at deeper levels for groundwater flow. The magnetic profiling carried out along various profiles has indicated the presence of buried dykes.

Since the groundwater in the weathered zone is almost dry and it was essential to delineate the saturated fracture zones. Though the fracture zones (which are thin compared to their depth of occurrence) could not be identified in the resistivity sounding as separate layers, their presence was identified in well logging and their extension could be found through Mise-a-la-masse and SP surveys. Thus, a joint interpretation of various geophysical surveys including resistivity and magnetic profiling across the dolerite dykes has provided a clear conceptualization of the aquifer geometry, inferred variation in various aquifer properties controlling flow and storage in the aquifer such that an appropriate aquifer model could be prepared. The study clearly analyses that with single parameter geophysical surveys, it was not possible to reduce a number of crucial ambiguities.

REFERENCES

Krishnamurthy NS, Kumar D, Negi BC, Jain SC, Dhar RL, Ahmed S (2000) Electrical Resistivity investigation in Maheshwaram Watershed, AP, India, Technical Report No NGRI-2000-GW-287

Kumar D, Krishnamurthy NS, Ahmed S, Jain SC, Dhar RL (2003) Mise-à-la-masse technique in establishing the lateral extension of fractures in hard rocks, Journal of The Geological Society Of India 61(2):185-194

Flow model relevant to fractured crystalline aquifers: insights from a scaling interpretation of pumping tests

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A b s t r a c t : Field observations show that fractured media are heterogeneous on a broad range of scales. To investigate if a mean hydrological model consistent with such a complex aquifer structure could be defined, we performed a series of pumping tests in a fractured bedrock aquifer and observed the drawdown on a network of piezometers. Pumping tests are particularly well designed to track scaling effects since the growth of the radius of influence is a way to sample average permeability over scales. We consider the interpretation frameworks underpinned by equivalent media that account for the multiscale fractured media heterogeneity. Results show that a fractional flow model with a flow dimension in the range [1.4-1.7] is appropriate for the whole site. In all cases, it much better predicts the late time drawdown evolution than Theis model. The scale evolution of the characteristic time and of the amplitude of the pressure drawdown shows also that diffusion is anomalously slow. Although the flow dimension is well defined for the whole site, the model that accounts for anomalous pressure diffusion is depending on the characteristics of the two main site-scale heterogeneities.

Field studies have shown that natural fracture networks are heterogeneous on a wide range of scales because of the presence of fractures from the milimetric to the kilometrical scale (Bonnet *et al.* 2001, Bour *et al.* 2002). In fact the presence of heterogeneity at virtually all scales of the medium induces an extreme flow channeling and the scale dependency of the equivalent hydraulic properties (Bour and Davy 1997, de Dreuzy *et al.* 2002). As a consequence, the application to fractured media of the homogeneous and classical porous media models is severely called into question.

We aim at characterizing the mean hydrological model consistent with the complex aquifer structure. We especially focus on permeability scaling that is supposed to result from the spatial integration of heterogeneities. Pumping tests are particularly well designed to track these scaling effects since the growth of the radius of influence is a way to sample average permeability over scales. In section 1 we describe the site of Ploemeur where we have performed a series of pumping tests. In section 2, we present the well-test interpretation frameworks and their underlying assumptions of hydraulic properties. In section 3, we give the results from assessing the proposed models on drawdown data.

MULTISCALE PUMPING TEST DATA

We have extensively studied a crystalline aquifer in Brittany (France) by performing well tests and monitoring drawdowns at several observation piezometers located at distances ranging from 2 m to 400 m from the pumping well (fig.2). To analyze the transient response of the site, we used long term (up to 90 days) and detailed short term (5 days) pumping tests. Thanks to this broad scale range, we are able to test the relevance of equivalent models. This aquifer is exploited at a rate of about 10^6 m^3 per year. The producing wells are located at the contact of two main tectonic features: a gently dipping contact zone between granite and micaschist formations that may be locally highly fractured and a subvertical normal fault (fig.1).

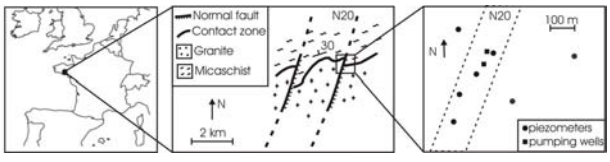

Figure 1. Geographical situation, geological model of the site and location of piezometers

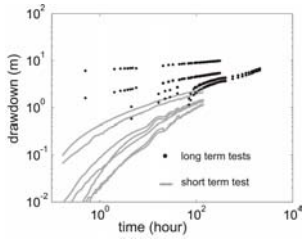

Figure 2. Drawdown observations for short term, medium term and long term pumping tests

INTERPRETATION FRAMEWORK FOR MULTISCALE FRACTURE NETWORK PROPERTIES

Interpreting the drawdown curves in terms of property scaling requires a fitting model that includes the hydraulic scaling properties of the medium. The simple although commonly used Theis model (Theis 1935) implicitly assumes scale-independent permeability and storativity. The dual-porosity model (Barenblatt *et al.* 1960), although more sophisticated, also assumes an independence of permeability with scale. Both these models are found to be inconsistent with most of drawdown curves observed in natural fractured rock fields (Bangoy *et al.* 1992, Hamm and Bidaux 1996, Leveinen 2000). New models have been developed to explicitly account for the scale dependency of the medium hydraulic properties (Barker 1988, Acuna and Yortsos 1995). The generalized radial flow model of Barker (1988) generalized the radial flow equation for non-integral dimensions by assuming that flow takes place through a n-dimension sphere. The so-called flow dimension n can take values between 1 and 3. The equivalent model of Acuna and Yortsos (1995) is another generalized model that was set up on deterministic fractals. It accounts for anomalously slow diffusion and turns out to generalize Barker's model.

Based on geological data and on the multi-scale fractured medium heterogeneity, these models have however never been fully verified on natural examples, mainly because of the lack of extensive data sets at different scales. In fact the model assessment requires observation of drawdowns at different scales on a sufficient range of spatial and temporal scales.

The diffusion equations of Theis' model, Barker's model and Acuna and Yortsos' model are similar and have the same general analytic solution for the drawdown:

$$s(r,t)=h_0(r).\Gamma\left(\frac{n}{2}-1,\frac{t_c(r)}{t}\right), \qquad (1)$$

where Γ is the (complementary) incomplete gamma function.

This solution has got three parameters: n, the flow dimension, t_c the characteristic time and h_0 the characteristic amplitude. The evaluation of the relevance of these models for natural cases consists in comparing the drawdown observed on the field to their solution given by (1). If the shapes are consistent, the three parameters h_0, t_c and n can be obtained by a single fit to the data. n is determined by the late-time shape of the curve and h_0 and t_c are determined respectively by the vertical and horizontal shifts of the curve. Barker's and Theis' models can be distinguished by the value of n : n=2 for Theis' model and 1<n<3 for Barker's model. Barker's and Acuna and Yortsos' models can be distinguished by the evolution of t_c on piezometers located at different distances from the well, as $t_c \sim r^{d_w}$. In fact, in Barker's model, diffusion is normal, d_w=2, whereas in Acuna and Yortsos' model diffusion is anomalously slow with d_w>2. The pertinence of Barker's and Acuna and Yortsos' models thus requires the existence in the field of a network of piezometers located at different distances from the pumping well spanning the widest possible scale range.

ASSESSMENT OF MODELS

The drawdown data is fitted with the Barker's fractional flow model (1), providing the desired values of hydraulic dimension, characteristic time and amplitude. Whatever the pumping test duration and whatever the distance to the pumping well, the fractional flow dimension deduced is found in the range 1.4-1.7 (fig.3). Fig.4 shows a typical drawdown observation where both Theis model (n=2) and a fractional model (n=1.6) are fitted to the data. The Theis model can not fit both the data and their derivative particularly at late times.

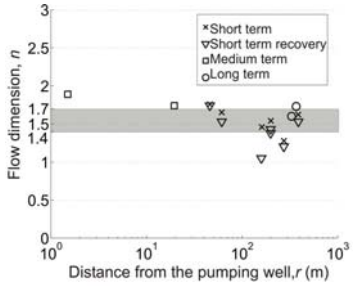

Figure 3. Evolution of flow dimension *n* with distance to the pumping well, *r*

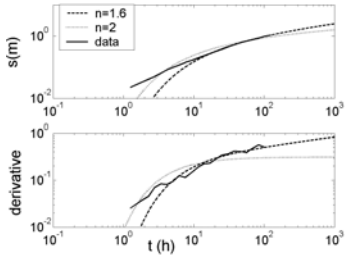

Figure 4. Comparison of best fit for *n=2* and *n=1.6*. The drawdown curve s s(t) and derivative curve are presented

The study of high resolution short-term pumping tests yields estimations of characteristic arrival time of the pressure signal for seven piezometers located at different distances from the pumping well. Note that the values of t_c at different piezometers can be compared only if they are obtained for the same value of the hydraulic dimension n. We thus took n=1.6 corresponding to the mean value of the estimations. The scale evolution of the characteristic time is anomalously slow in agreement with *Acuna and Yortsos*' model (fig.5). This is confirmed by the scale evolution of the characteristic amplitude.

In terms of pressure diffusion, the wells that intersect only the contact zone between granite and micaschist and the wells that are within the subvertical normal fault zone have a different hydraulic response. A unique set of parameters that would have implied the relevance of a global transient flow model can be defined only for the zone around the normal fault where most piezometers are located, for which we obtain d_w=2.8 (fig.5). The two wells away of the N20 fault do react differently according to larger scale geologic structures.

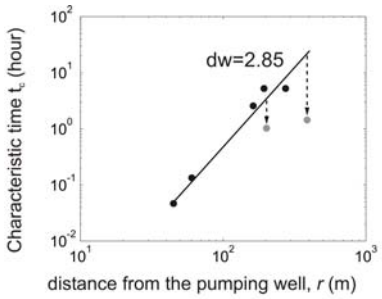

Figure 5. Evolution of tc with distance for the short term test (n set to 1.6)

CONCLUSION

An extensive pumping test dataset is available at the Ploemeur fractured rock site. The large spatial and temporal distribution of drawdown observations provides an opportunity to assess the relevance of a mean equivalent flow model.

Along the N20 fault (fig.1), it is possible to define an equivalent mean flow model. Flow can be characterized by a fractional flow dimension (n=1.6) and by an anomalously slow diffusion of pressure (d_w=2.8).

REFERENCES

Acuna JA, Yortsos YC (1995) Application of fractal geometry to the study of networks of fractures and their pressure transient. Water Resources Research 31(3):527-540

Bangoy LM, Bidaux P, Drogue C, Plegat R, Pistre S (1992) A new method of characterizing fissured media by pumping tests with observation wells. Journal of Hydrology 138(1-2):77-88

Barenblatt GI, Zheltov IP, Kochina IN (1960) Basic concept in the theory of seepage of homogeneous liquids in fissured rocks. J Appl Math 24:1286-1303

Barker JA (1988) A generalized radial flow model for hydraulic tests in fractured rock. Water Resources Research 24(10):1796-1804

Bonnet E, Bour O, Odling N, Main I, Berkowitz B, Davy P, Cowie P (2001) Scaling of Fracture Systems in Geological Media. Reviews of Geophysics 39(3):347-383

Bour O, Davy P (1997) Connectivity of random fault networks following a power law fault length distribution, Water Resources Research. 33(7):1567-1583

Bour O, Davy P, Darcel C, Odling N (2002) A statistical scaling model for fracture network geometry, with validation on a multiscale mapping of a joint network (Hornelen Basin, Norway). Journal of Geophysical Research 107(B6)

de Dreuzy JR, Davy P, Bour O (2002) Permeability of 2D fracture networks with power-law distributions of length and aperture. Water Resources Research

Hamm S-Y, Bidaux P (1996) Dual-porosity fractal models for transient flow analysis in fissured rocks. Water Resources Research 32(9):2733-2745

Leveinen J (2000) Composite model with fractional flow dimensions for well test analysis in fractured rocks. Journal of Hydrology 234(3-4):116-141

Theis CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Transactions of American Geophysical Union 16:519-524

Pump tests analysis in fissured media: combination of fractional flow with double continuum approach and leakance

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A b s t r a c t : The identification of the hydraulic and transport properties of fractured aquifers requires the development of models that account for (1) the presence of major conductive fractures that delimit capacitive matrix blocks and (2) the geometrical characteristics of the fractures network, which controls the flow at the scale of the pump tests. These two main features are tackled by combining generalized radial flow (flow with fractional dimension), with double-porosity and leakance approaches, tacking into account pumping well storage and skin effects. The various behaviours are illustrated with examples of distinctly different field experiments conducted in sedimentary and crystalline rocks.

INTRODUCTION

The leakance concept applies to semi-confined aquifers, under or overlying an aquitard, for which the exchanges with the well are considered negligible. The double porosity approach considers that the system can be represented by two overlapping continua: (1) the main fissures network which dominates the flow at the scale of the influence volume, and (2) the blocks, drained by the fissures that may contain poorly connected fissures. Inter-continua exchange can be either stationary or transient. The former has been enriched by the parameterization of the fissure skin effect (Moench 1984), due to the hydraulic impedance of the mineral deposits on the fissures faces. When this impedance becomes important, Moench's solution reduces to the stationary exchange. Hence we consider here only the transient exchange with fissure skin effect, which generalizes the possible exchanges between blocks and fissures.

Fractional flow dimensions find their usefulness when integral dimensions (1, 2, 3) solutions are not satisfying. Barker's solution (1988) for one continuum has been extended to leakance and double porosity systems (Hamm et Bidaux 1996). In sufficiently fissured media, the flow around pumping wells is dominated by the intercepted discontinuities network. The flow dimension constitutes a parameter, reflecting the dominating geometry of the flow in the network. For example, this parameter is 1 for a parallel flow (subvertical fault intercepted by the well, or one channel fissure), 2 for cylindrical flow (fully penetrating well in a homogeneous porous aquifer as Theis's model), and 3 for spherical flow (packer tests with one intercepted fissure in a dense and extended network). For all combinations of these geometries, generalization to fractional dimensions is necessary.

Wellbore skin effects, which are potentially important, can be taken into account. They include laminar and turbulent head losses occurring in the hole, its equipment and in the close vicinity of the well. Once the well has been developed, or when the fissures are well open at the well face, a relative head gain, called negative skin effect, can be observed. Additionally, well storage effect, due to the difference in storage and conductivity between the zone occupied by the well and the formation, can be accounted for.

GOVERNING EQUATIONS

The models above assume a confined isotropic aquifer, radialy infinite and initially at rest. Each continuum is homogeneous. Under the leakance assumption, the drawdown in the network h_f (m) obeys the equation:

$$S_{sf}\frac{\partial h_f}{\partial t} = \frac{K_f}{r^{n-1}}\frac{\partial}{\partial r}\left(r^{n-1}\frac{\partial h_f}{\partial r}\right) + K_f\frac{h_f}{B^2} \qquad (1)$$

where K_f (m./s^1) and S_{sf} (m^{-1}) are the hydraulic conductivity and specific storativity of the fissures network respectively, r (m) is the radial distance from the well, B (m) is the leakance factor, which characterizes the exchanges with the aquitard, and n is the flow dimension. Under the double porosity assumption, drawdowns in the network and in the blocks, h_m (m), obey the equations:

$$S_{sf}\frac{\partial h_f}{\partial t} = \frac{K_f}{r^{n-1}}\frac{\partial}{\partial r}\left(r^{n-1}\frac{\partial h_f}{\partial r}\right) + \frac{K_m}{b_m}\left(\frac{\partial h_m}{\partial z}\right)_{z=0} \qquad (2)$$

$$S_{sm}\,\partial h_m/\partial t = K_m\,\partial^2 h_m/\partial z^2 \qquad (3)$$

where K_m and S_{sm} are the hydraulic conductivity and specific storativity of the blocks respectively, z (m) is the coordinate in the block on the draining path ($z = 0$ at the interface), b_m (m) is the mean length of the draining paths, or blocks mean half thickness ($\partial h_m/\partial z = 0$ for $z = b_m$). In place of S_{sm}, K_m, b_m and z, it is usual to consider the dimensionless parameters:

$$\omega = \frac{S_{sf}}{S_{sf}+S_{sm}} \qquad \lambda = \frac{K_m r_w^2}{K_f b_m^2} \qquad z_D = z/b_m \qquad (4)$$

The hydraulic impedance of the mineral deposits on the fissure walls, is modelled as a singular head loss characterized by the fissure skin factor σ_f (-):

$$h_m(z=0) = h_f + b_m\sigma_f\left(\partial h_m/\partial z\right)_{z=0} \qquad (5)$$

The exchanges between the well and the blocks are minor compared to its exchange with the fissures network. The balance equation is:

$$S_w\,\partial h_w/\partial t = \mathrm{Q} + K_f b_f^{3-n}\alpha_n r_w^{n-1}\left(\partial h_f/\partial r\right)_{r=r_w} \qquad (6)$$

where h_w (m) is the well drawdown, b_f (m) characterizes the ortho-radial extent of the flow front, which is the aquifer thickness in dimension 2. The α_n coefficient is equal to $2\pi^{n/2}/\Gamma(n/2)$ where Γ is the gamma function, Q (m^3/s) is the test rate, S_w (m^2) is the well capacity, which for a test without packer, corresponds to its free surface area. For tests with packers, S_w characterizes their deformability. The exchange radius r_w (m) is the inner radius of the well, in the zone of exchange with the aquifer. The well skin effects are represented by a singular head loss, through the well skin factor σ_w (-):

$$h_w = h_f(r_w) + r_w\sigma_w\left(\partial h_f/\partial r\right)_{r=r_w} \qquad (7)$$

A negative value of σ_w indicates a good fissures opening at the well face. Drawdown in the well and in the continua are obtained analytically in the Laplace domain, and numerically transformed in the time domain using Stehfest's algorithm.

FIELD EXAMPLES

Example 1 shows an application of high dimensions and leakance flows emphasizing their similar behaviour. The L1 hole, drilled in the limestones has been tested at 3 flow rates (fig.1). Drawdown curves suggest leakage effects, or a high dimension flow. The first pump step shows fully stabilized curves, whereas step 3 does not. This can be explained by the onset of a conduct, unsaturated during step 1, and saturated during step 3. With

identical K_f, S_{sf}, b_f, one attain the same global quality level, by considering a simple leakance or a flow dimension of 2.25. Step 1 is slightly better fitted with simple leakance, while the others are slightly better fitted with a dimension of 2.25. With a dimension of 2.5, step 1 can be fitted as well as with simple leakance, but the other steps are worse fitted.

Example 2 is an application of the low dimensions. The SB and SBT holes are drilled in the harzburgites of an ophiolitic complex (fig.2). Modelling drawdowns using cylindrical flow requires the introduction of tight boundaries. With fractional flow, this type of behaviour can be interpreted using a very low dimension. The better fit is obtained for a dimension of 0.7, considering that the piezometer intercepts the fissures network of a double porosity medium. The very low dimension indicates a possible anisotropy and/or the presence of multiple impervious boundaries. The high value for λ ($4.87\ 10^{-5}$) indicates an important blocks permeability, while the value of σ_f indicates a substantial head loss at the blocks-fissure interface, possibly due to mineral coating.

Example 3 shows a relevant application of fractional flow in fissured gabbros (fig.3). The site comprises a pumping well and three piezometers. With a dimension of 2, none of the curves can be fitted accurately, whereas a dimension of 1.7 allows fitting simultaneously three of the four curves with exactly the same parameters. The last one implies only to add a tortuosity coefficient slightly larger than 1, possibly linked to higher flow path heterogeneity in that direction.

Example 4 is an application to a pumping test in fissured granites showing atypical results. The two piezometers (IF11 and IF12), located at the same distance from the pumping well IF1, react at the same time, but with different amplitudes (fig.4). They are located symmetrically apart from the well, thus their behaviour difference cannot be explained by anisotropy. The fit was performed by considering IF12 and IF11 in distinct continua. The best fit is obtained for a dimension of 1.8. In this case IF1 and IF12 are very well fitted at all time, whereas only the last ten hours of IF11 can be completely fitted. That can be explained by the de-saturation, during the test, of a sub-domain of the fissures network that was initially saturated.

CONCLUSION

These combined models set greatly generalize the usual double-porosity and leakance 2D models unifying 1D, 2D and 3D approaches in a *n*D model, with *n* been a real number, tacking into account pumping well storage and skin effects. Although not considering the fissures geometry and properties one by one, or by directional families, their presence is taken into account by averaged properties and by the impact that the whole network has on the hydrodynamic behaviour. In many cases, these generalised models give a very powerful analysis tool at the scale of pumping tests. In particular, the combination of double continuum approach with fractional flow offers a wide range of behaviours with a limited number of parameters, allowing an accurate match of the data, and, as a consequence, an improved prediction.

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REFERENCES

Barker J (1988) A generalized radial flow model for hydraulic tests in fractured rock. Water Resources Res 24(10):1796-1804

Hamm S, Bidaux P (1996) Dual-porosity fractal models for transient flow analysis in fissured rocks. Water Resources Res 32(9):2733-2745

Moench A (1984) Double porosity models for a fissured groundwater reservoir with fracture skin. Water Resources Res 20(7):831-846

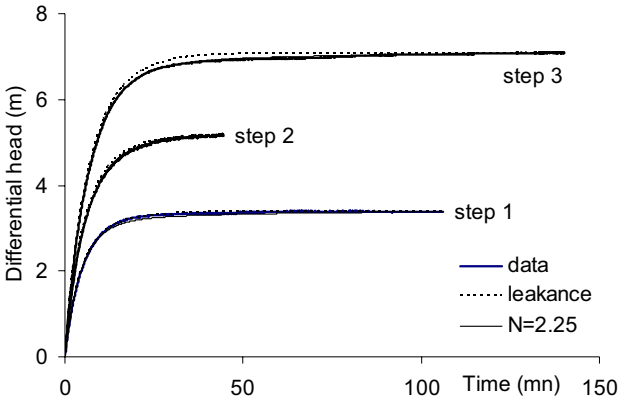

Figure 1. Step drawdown test in limestones (hole L1)

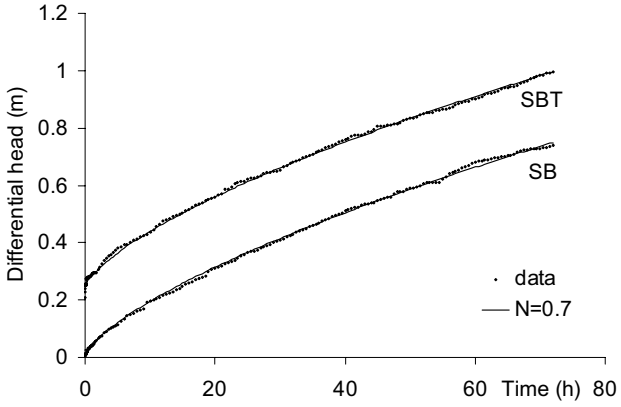

Figure 2. Pump test in harzburgites

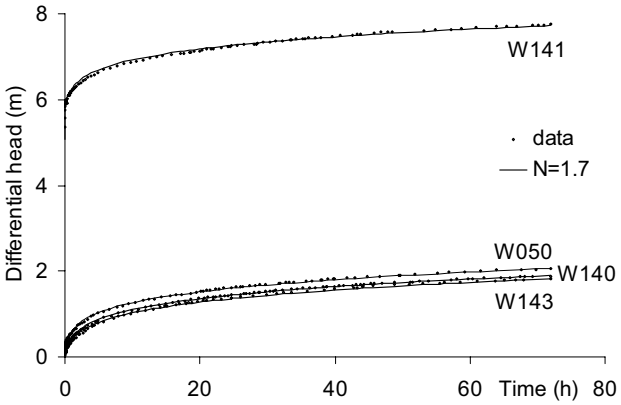

Figure 3. Pump test in gabbros

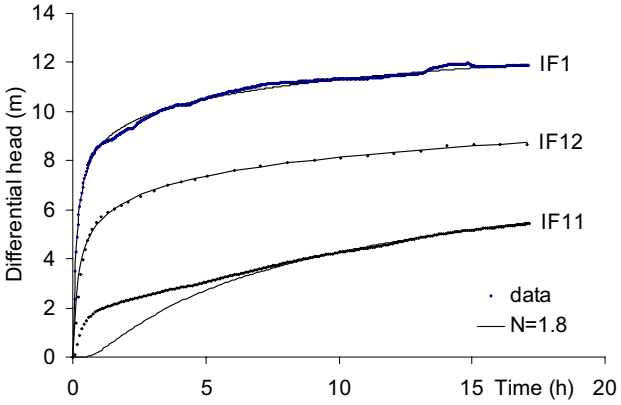

Figure 4. Pump test in granites

Well Dilution: a new method to identify flow zones and relative horizontal flow rates in a well

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A b s t r a c t : Locating active hydraulic fractures and estimating groundwater flow rates in heterogeneous aquifers is difficult and usually requires detailed and costly field investigations. We present a new cost effective method for locating major fractures and estimating relative horizontal flow rates at different depths within a well. The technique is an adaptation of the point dilution method, but requires no inflatable packers. The method requires a contrast in a physical or chemical parameter between an ambient well profile and a tracer profile. Groundwater in a well is mixed by circulating water from the bottom of the well to the top and then the concentration profile is monitored over time as it is replaced by aquifer water moving through the well until it returns to its original ambient profile. If the well is stratified with respect to some tracer, such as electrical conductivity only mixing of the well is required to undertake the test. Alternatively, a tracer (such as NaCl) can be added during mixing. The time required for the mixed profile to return to the initial profile is related to the groundwater flow rate.

INTRODUCTION

Contamination of heterogeneous aquifers has seen the development of new techniques to estimate groundwater flow rates over small spatial scales where the interest is on estimating contaminant velocities within individual fractures (NRC 1996). One of the most useful techniques, originally developed for porous medium aquifers (Drost *et al.* 1968). Normally, point dilution tests require that packers isolate an interval of interest. To obtain a complete profile of horizontal flow over the length of a well using the point dilution method requires numerous costly tests. In this paper we describe an adaptation of the point dilution test, for estimating flow rates that requires only a single well and no packer installations. The objective of this work is to develop a cost-effective field technique where fracture locations and relative flow rates through a well can easily be determined in the field by visual inspection of concentration-time profiles. We also demonstrate the potential for estimating flow rates using this approach by the development of a compartmental mixing cell (CMC) model.

POINT DILUTION

The point dilution method is based on injecting a tracer into an interval of a well isolated by packers and monitoring the concentration of the tracer with time as it is flushed by regional groundwater flow. The groundwater flow rate is related to the time it takes for the tracer to be removed from the test interval. The faster the tracer is removed the faster the horizontal flow. For a perfectly mixed well the changes in concentration within the well can be expressed as:

$$C(t) = C_\infty + (C_\infty - C_O)\exp\left[\frac{-2qt}{\pi r}\right] \quad (1)$$

where, C = concentration in the test interval [ML^{-3}], t = time measured after injection of the tracer, C_∞ is the concentration in the well prior to injection of the tracer (assumed to be equal to the concentration in the aquifer in the vicinity of the well), C_o = concentration of the tracer in the well immediately after injection, q is the horizontal flow rate (or Darcy velocity) through the test interval (assumed to be constant throughout the duration of the test) [LT^{-1}]. The important assumption of the test is that the tracer concentration (C_o) is completely mixed through the entire packed-off volume for the entire test.

WELL DILUTION

The Well Dilution test is an adaptation of the point dilution tests but covers the entire well. The well column is disturbed by pumping water from the bottom of the well and re-injecting it into the top of the well (so that no water is removed from the well). The method requires a contrast in concentration between water in the well, C_∞ and a tracer C_o. For aquifers where groundwater EC increases with depth no added tracer is required. For cases where there is no stratification of EC in the well a concentrated tracer such as NaCl is slowly added into the injection line for the whole time the well is pumped. The pump is quickly removed and EC is monitored at different times as it returns to its pre mixed concentration.

Unlike standard point dilution tests this method seeks to examine changes in flow rate with depth, rather than to mix packed off zones and measure a mean flow rate for the interval. Horizontal flow into the well can be estimated by monitoring the time required for the mixed profile Co to return back to its original concentration C∞. When Co approaches C∞ rapidly, high horizontal flow can be inferred. Conversely low horizontal flow is inferred when Co returns slowly to C∞. Under conditions of horizontal flow the changes in concentration with time at each depth should be given by equation (1). If vertical flow is important then quantification of horizontal flow rates is more difficult and requires numerical modelling. The advantage of the method is that the location of major fractures and flow zones can be readily identified over the entire well column.

As the well acts as a zone of high hydraulic conductivity, flow lines will converge towards the well. For a well open to the aquifer with no well skin the flow through the well is twice as large as that through the aquifer (Drost *et al.* 1968).

FIELD SITE AND METHODS

The field site is the Wendouree Winery in the Clare Valley an important viticulture region located approximately 100 km north of Adelaide, South Australia (33°50'S; 138°37'E). Groundwater occurs in a fractured carbonaceous dolomite of low matrix porosity and permeability. Precipitation is 650 mm/yr and ET is ~ 1975 mm/yr (Love e*t al*. 2002).

Well Dilution experiments were performed in October 1998 and May 2000 (chosen to represent seasonal variation in the water table, 4 m below the ground surface in October and 8 m in May). In these experiments we did not add tracer but took advantage of the natural EC stratification in the well. For both experiments the well was disturbed by pumping relative saline water from ~ 90 m and re-introducing the water at the top of the well. The experiments resulted in an inversion of the original EC

profile with more saline water stratified over lower salinity water. EC was monitored in vertical profile at different time periods from 15 minutes (immediately after removing the pump) until 15 days as it returned to its pre-mixed profile. In both experiments it was not critical to obtain a perfectly mixed well profile, rather what is important is to obtain a disturbed concentration profile (C_o) that is significantly different to the ambient concentration profile (C_∞).

The tests can be examined qualatively by examining the time taken for $C_o \rightarrow C_\infty$. In order to obtain semi-quantative estimates of flow a compartmental mixing cell (CMC) was developed to separate the effects of horizontal and vertical flow. The well is divided into a one-dimensional vertical domain that is discretized into a number of cells. Each cell receives inputs of mass (water and solute) both horizontally from the aquifer and vertically from the well. Further details of the modelling approach will be presented elsewhere.

RESULTS

The results of the Well Dilution experiments and CMC modelling are shown in Fig.1. Here only the May 2000 test is discussed in detail. Flow is relatively rapid and appears predominantly horizontal in the top 38 m of the well, although less rapid than in October 1998 when the water table was higher. Below 38 m, horizontal flow decreases significantly. Below 70 m there is component of vertical flow in the bore from a source below 98 m. This upward flow is calculated to be approximately 1.1 m/day from the temporal changes in the EC profile.

An inspection of the EC profiles provides evidence for the location of active fractures at depths of 17, 22, 28 and 38 m based on troughs in the original mixed profile (C_o). The initial EC profile was first logged 15 minutes after mixing, however even at this early time the fluid in the well is being diluted by aquifer water at a rapid rate. At later times these deviations become less obvious due to dispersion within the well.

A CMC model was run for different time periods in order to simulate the transient behaviour of the EC profiles. Model calibration was achieved by adjusting horizontal and vertical flow rates for each cell until the modelled EC profiles fitted the field data (C_i). The results of the model calibration For May 2000 was for 0.4 days since mixing, which yields an R^2 of 0.98 between the field data and the simulation. Horizontal flow is shown to vary by over 3 orders of magnitude. The mean flow through the well was calculated to be 11.7 m^2/day, of which 85 % occurs in the top 40 m of the aquifer.

CONCLUSIONS

Estimating groundwater flow rate is notoriously difficult. As aquifer heterogeneity increases so does the difficulty in calculating flowrates using conventional techniques. We have developed a new technique the Well Dilution method that eliminates some of the these difficulties by providing a direct measurement of groundwater flow without prior knowledges of aquifer propertoies. The Well Dilution tests locates flowing hydraulic fractures and determines relative horizontal flow rates throughout the well something not previously feasible.

REFERENCES

Drost W, Klotz D, Koch A, Moser H, Neumaier F, Rauert W (1968) Point dilution methods of investigating ground water flow by means of radioactive isotopes. Water Resour Res 4(1):125-46

Love AJ, Cook PG, Harrington GA, Simmons CT (2002) Groundwater flow in the Clare Valley. Department for Water Resources, South Australia. Report DWR02.03.0002, 43 pp

National Research Council (NRC) (1996) Rock fractures and fluid flow:Contempoary understanding and applications. National Acadamy Press, Washington DC, 551pp

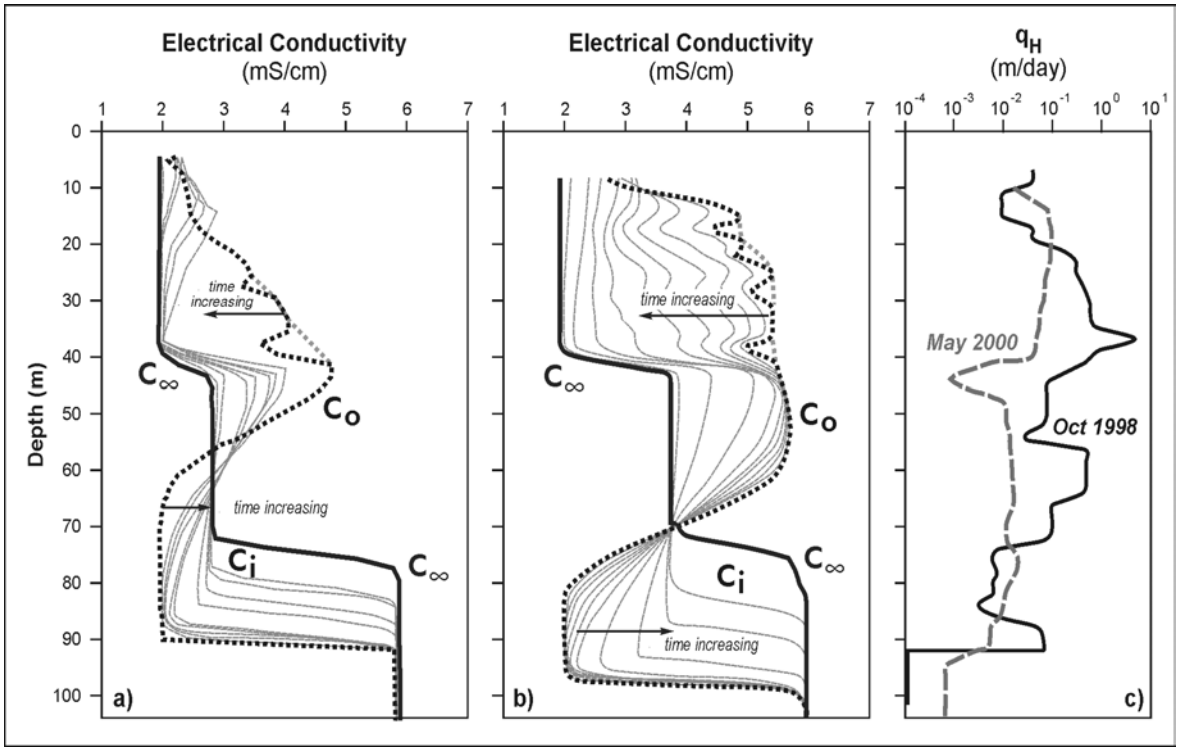

Figure 1. Results of Well Dilution experiments. a) October 1998, b) May 2000. The initial EC profile before mixing is denoted C_∞, (solid thick line) which is assumed to reflect the EC profile in the aquifer. The initial profile immediately after mixing is denoted C_o (dashed thick line) and the transient EC profiles (C_I, dashed thin lines) as they evolve at different times after mixing. Arrows denote increasing time. c) Results of the CMC modelling for horizontal flow through the well.

Laboratory visualization of two-phase flow in a natural fracture by neutron tomography

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A b s t r a c t : Due to their weak interaction with matter, thermal neutrons are highly penetrating and can be used as a non-destructive probe for complex structures. As water has a high macroscopic cross section, neutron radiography is suitable to investigate moisture content of rock samples. We use neutron tomography to visualize imbibition and drainage in a core containing a fault-gouge filled fracture. The experiments show that after drainage the water is very irregularly distributed, supporting that air flows through preferential paths. During capillary imbibition the wet front rises rapidly. After a few minutes it assumes an almost steady-state profile and then a slow increase of moisture content in the already wet regions is observed. We suggest that water first fills a well-connected porosity then it is slowly sucked into a poorly connected porosity.

INTRODUCTION

Heterogeneity of fracture properties may yield unevenly distributed multiphase flow and transport. The behaviour of the system strongly depends on the pore-volume distribution and the nature of the heterogeneities (Lunati *et al.* 2003; Lunati 2003). In case of a complicated structure such as a shear zone in crystalline rocks, it is desirable to directly observe flow and transport phenomena and assess whether the flow takes place in few preferential paths or is evenly distributed over the whole fracture.

Non-destructive investigation of two-phase flow in a granite core was attempted by Chen and Kinzelbach (2002) by nuclear magnetic resonance (NMR). However, due to the paramagnetic properties of granite, only low-intensity magnetic fields can be applied, which do not allow high resolution: only an overall pore-size distribution can be measured reliably. A technique that allows better spatial distribution is neutron radiography. This technology was used in the past to investigate the moisture distribution in different materials (Lehmann and Vontobel 2000; Pleinert *et al.* 1998; Pleinert and Degueldre 1995; Degueldre *et al.* 1996). We use neutron radiography to investigate two-phase flow in a core containing a fault-gouge filled fracture. We study both capillary imbibition in the dry sample and drainage by air injection in the saturated sample (see also Lunati 2003).

NEUTRON RADIOGRAPHY: THEORETICAL BACKGROUND AND TECHNOLOGY

The transmission behaviour of a neutron beam can be described by the simple exponential attenuation law, i.e. $I = I_0 \exp(-\Sigma d)$, where I is the intensity of the transmitted beam [n/cm^{2}s], I_0 the intensity of the incident beam [n/cm^{2}s], d the thickness of the sample [cm], and Σ the macroscopic cross section [cm^{-1}]. (Deviations have to be expected and taken into account for thick samples or strongly interacting material.) Since different materials have a different macroscopic cross section, by comparison between the incident and transmitted beams, we can obtain information about the sample composition. Due to the high macroscopic cross section of water, neutron radiography represents a powerful tool to investigate moisture distributions.

Our experiment is performed at the NEUTRA radiography facility of the Paul Scherrer Institute in Villigen (AG, Switzerland – http://neutra.web.psi.ch/). The incident beam of thermal neutrons is produced by the spallation source SINQ; it has a neutron flux of 7.7 10^6 n/cm^{2}s and a collimation ratio of 350. The transmitted beam is recorded by a Peltier cooled CCD camera as a 2D projection of the object with a spatial resolution of 115×115 μm^2 determined by the camera lens used. The sample is fixed on a rotating table, which permits a rotation in small angular steps over 180° and allows the reconstruction of fully 3D information from the 2D projections by computed tomography (CT).

THE FRACTURE SAMPLE

The core was drilled in the Grimsel Granodiorite at the GAM experimental site in the Grimsel Underground Laboratory (BE, Switzerland). At the upper face four fractures are visible, which contain a non-cohesive fault gouge material. A preliminary x-ray CT investigation was performed in order to assess the internal structure of the core and choose a fracture for the experiments, which is well separated from the others. This allows performing the two-phase flow experiment in a single fracture. Then, the sample is sub-cored (diameter of about 80 mm) and an aluminium tube is molded to the sub-core, the two vertical boundaries of the selected fracture being previously sealed (at least partially) with mortar in order to prevent a significant secondary flow between Al-tube and granite. After drying at 40°C for about two weeks, a layer of silicon is spread on the two faces of the sample except the area corresponding to the fracture that is selected for the experiment. This is intended to seal the other fractures, as well as the space between the Al-tube and the core, and make them impermeable to the flow.

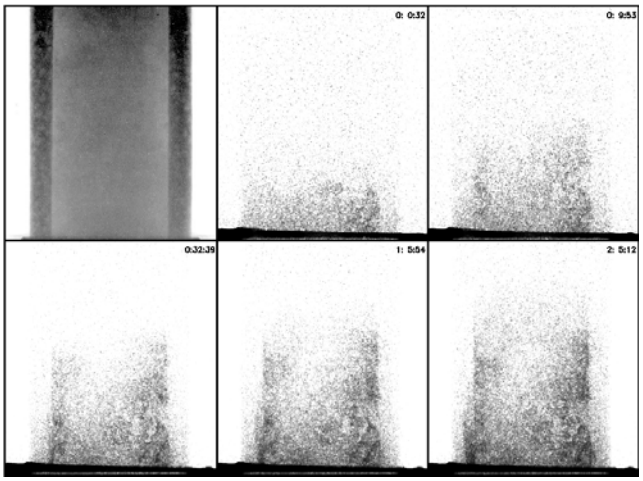

Figure 1. Top-left corner: Dry-sample radiography, projection in the direction perpendicular to the flow. Top center to bottom-right corner: ratios of the radiography at different times after capillary imbibition started and the dry sample radiography (top-left corner). These ratios show the water content (black) in the core at times 32sec, 9min 53sec, 32min 39sec, 1h 5min 54sec and 2h 5min 12 sec after the the bottom of the sample was brought in contact with water

EXPERIMENTAL PROCEDURE

Capillary imbibition

A first experiment is aimed of visualizing the capillary rise of water in the dry sample. By comparing the transmission of neutrons through the sample before and after imbibition, we obtain information on the water distribution. Due to the thickness of the core, a relatively long exposition time (around 40 sec) is needed in order to guarantee an adequate intensity of the transmitted beam and a satisfactory image resolution.

After acquisition of fully three-dimensional information by tomographic reconstruction, the bottom of the sample is brought

in contact with water and capillary suction starts. We observe the wetting front displacement by 2D radiographies. Each image acquired at a certain time step is normalized by the radiography of the dry sample, such that differences from the dry state are highlighted and water distribution results (fig.1). The front rises rapidly and after a few minutes the water appears irregularly distributed. After that, an increase of moisture content in the already wet regions is observed. We suggest that this reflects non-negligible conductivity effects during unsteady imbibition: even if the height of the capillary rise is completely determined by capillarity, imbibition might be slower if conductivity is low. We also observed a tendency for water to accumulate at the boundaries. Despite of the effort made in order not to disturb the fracture, we cannot completely exclude that the boundaries are perturbed during the core processing.

From 2 hours on, only slight variations are observed and the sample can be considered in a quasi-steady state. After 3 hours a tomographic image of the imbibed sample is acquired and compared with the tomography of the dry sample. It can also be observed that water is not uniformly distributed and air bubbles (visible as white spots) are present. This is due to the nature of the capillary force that sucks water into the small pores, whereas large pores are filled by air.

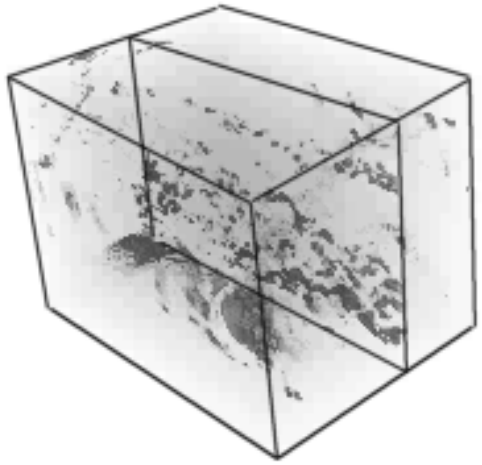

Figure 2. Ratio of the saturated-sample tomography to the drained-sample tomography for a selected volume. Black corresponds to higher water content in the saturated sample than in the drained sample, thus to regions drained by air injection. Fracture II is well visible and lies in a vertical plane in the middle of the volume

Water displacement by air injection

After the capillary-rise experiment, the sample is dried at 40°C for over a month. Then the core is saturated under vacuum conditions with degassed water und flushed for over 30 hours. A tomographic image is acquired, which shows the 3D distribution of the water phase in the sample. A non-complete saturation of the fracture selected for the experiment is observed: a few air bubbles are still entrapped in the fracture. In contrast, the other fractures are partially filled with water, despite of the silicon layer aimed to make them impermeable to the flow. The large amount of water in the saturated sample strongly reduces the transmission of neutrons and makes the signal to noise ratio worse than in the capillary-rise experiment. For these reasons little can be observed by 2D radiography and no satisfactory measurement of the air front displacement is achieved. Reconstruction of fully 3D information is necessary to achieve a satisfying resolution.

After draining the core for 1 hour by injecting air at 1.5 bar pressure, a tomographic image is acquired. By inspection of the entire 3D image no preferential path for air flow is observed at the boundaries. This suggests that the fracture boundaries were not disturbed by core processing, which would produce higher and better connected pores by flushing the fault gouge. We select a parallelepiped containing the fracture and we compute the ratio of the saturated-sample tomography to the drained-sample tomography. A representation of the result is shown in fig.2. The fracture is well visible and lies in a vertical plane in the middle of the volume. The darker regions correspond to higher water content in the saturated sample than in the drained sample, thus they represent the region drained by air injection. This is evidence that the air phase is unevenly distributed after drainage and testifies that air flows through preferential paths.

CONCLUSIONS

Neutron radiography offers a good tool for non-destructive investigation of granite samples. Due to the weak interaction with the core and the high macroscopic cross section of water, neutron radiography provides a good instrument for visualization of conductive paths: the water enhances the visibility of the porosity by strong attenuation of the neutron beam. This allows highlighting the part of the porosity, which takes part in a particular process.

A capillary imbibition experiment in a fault-gouge filled fracture shows that water is unevenly distributed. The water front rises rapidly and after a few minutes it assumes an almost steady-state profile. After that, a slow increase of moisture content in the already wet region is observed. We suggest that water rapidly fills a well-connected porosity and then it is sucked slowly into a poor-connected porosity. Since only 2D projections of the dynamic process are available because of temporal-resolution constraints, it is not easy to understand whether the poorly connected porosity consists exclusively of fault-gouge material or includes the granite matrix. Nevertheless, the much smaller connectivity and porosity (1.1% after Chen and Kinzelbach 2002) suggest that the amount of water imbibed into the matrix is negligible. This double porosity model is consistent with shrinking of the fault-gouge when drying, which has been observed (Chen and Kinzelbach 2002). We suggest that water first imbibes the channel opened in the dry sample by shrinking of the fault-gouge (well-connected porosity), than the fault-gouge itself, which represents the poorly connected porosity.

When the drainage experiment is performed by injecting air, the large amount of water in the saturated core and the rapid air breakthrough prevent us from observing the displacement of the air front. Despite of the effort to saturate only one of the four fractures in the core, water penetrates all of them, which yields a strong attenuation of the neutron beams such that fully 3D information is needed to obtain the necessary resolution and observe variations of the moisture content. After drainage the air phase in the fracture is very irregularly distributed, which testifies that air flows through preferential paths. This is consistent with the quick air breakthrough observed, which implies a very small air volume in the fracture.

REFERENCES

Degueldre C, Pleinert H, Maguire P, Lehman E, Missimeer J, Hammer J, Leenders K, Böck H, Townsend D (1996) Porosity and pathway determination in crystalline rock by positron emission and neutron radiography, Earth Planet Sc Lett 140(1-4):213-225

Lehmann EH, Vontobel P (2000) Investigation of hydrogen distributions in various base materials by neutron radiography methods, Proc. 15th World Conference on Non-destructive testing, Rome, Oct

Lunati I (2003) Conceptual Model of Single and Multiphase Flow in a Fracture, ETH Zurich, Ph.D. Thesis no. 15082

Lunati I, Kinzelbach W, Sørensen I (2003) Effects of pore volume-transmissivity correlation on transport phenomena, J Contam Hydrol (in press)

Pleinert H, Sadouki H, Wittman FH (1998) Determination of moisture distributions in porous building materials by neutron transmission analysis, Material and Structures 31:218-224

Pleinert H, Degueldre C (1995) Neutron radiographic measurement of porosity of crystalline rock samples: a feasibility study, J Cont Hyd 19:29-46

On-site determination of hydraulic conductivity in fractured rocks with double porosity

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A b s t r a c t : The water level motion in a piezometer can be initiated by compression or suction of the air in a sealed piezometer (slug-test, bail-test, paramex-test). The mathematical model of the free return of the water level to the static position comprises two cases of motion: damped oscillations and aperiodical (exponential) motion. However, during on-site examination of the hydraulic conductivity coefficient of fractured rocks using the paramex-test, an atypical case of the water level motion in the piezometer was encountered several times. The function $s = s(t)$ proved to be a superposition of damped oscillations and aperiodical (exponential) motion. It has been assumed that the filtered aquifer is characterized by double transmisivity in these cases. The oscillatory component of the water level motion characterizes the hydraulic conductivity coefficient of the fracture system. The aperiodical (exponential) component characterizes the hydraulic conductivity coefficient of the bed-rock. Theoretical considerations are illustrated by an example.

THE PARAMEX METHOD

The PARAMEX method enables on-site determination of hydraulic conductivity coefficient and permeability of the aquifer in the vicinity of the examined piezometer. It is also possible to apply it to evaluate the technical state of a piezometer. During piezometer examination by means of the PARAMEX method water level motion is initiated by air compression or suction in the sealed over well screen pipe. The rate of the motion depends both on hydrogeological parameters of the aquifer and on the construction parameters of the piezometer (Marciniak 2001). The goal of the measurement is to record the function $s = s(t)$ of the water level motion in the piezometer during both compressing and sucking of the air. PARAMEX can be considered as an "express" method of determining the hydraulic conductivity coefficient of aquifers among the *slug-bail test* group (Fetter 1994). The mathematical model of the free return of the water level to the static position comprises two cases: damped oscillations or aperiodic (exponential) motion.

ATYPICAL EXAMPLES OF WATER LEVEL MOTION IN FISSURE BODIES

An interesting case was observed in the C1 piezometer filtered in a gypsum capping over a salt dome in Wapno in the region of Wielkopolska (Poland). The water level motion is a superposition of two kinds of motion: damped oscillations and an exponential motion. The water level motion in an experiment with air suction is analogous (fig.1).

INTERPRETATION PROPOSAL

This atypical case of water level motion should be interpreted as an effect of double hydraulic permeability of fissure bodies (Małoszewski and Zuber 1985). The function $s = s(t)$ is then a superposition of damped oscillations and aperiodic (exponential) motion. The oscillatory component of the water level motion characterizes the hydraulic permeability of the fissure system. The aperiodic (exponential) component of the water level motion characterizes the hydraulic permeability of the bed-rock. In the initial phase of the water level motion an inflow of water into the

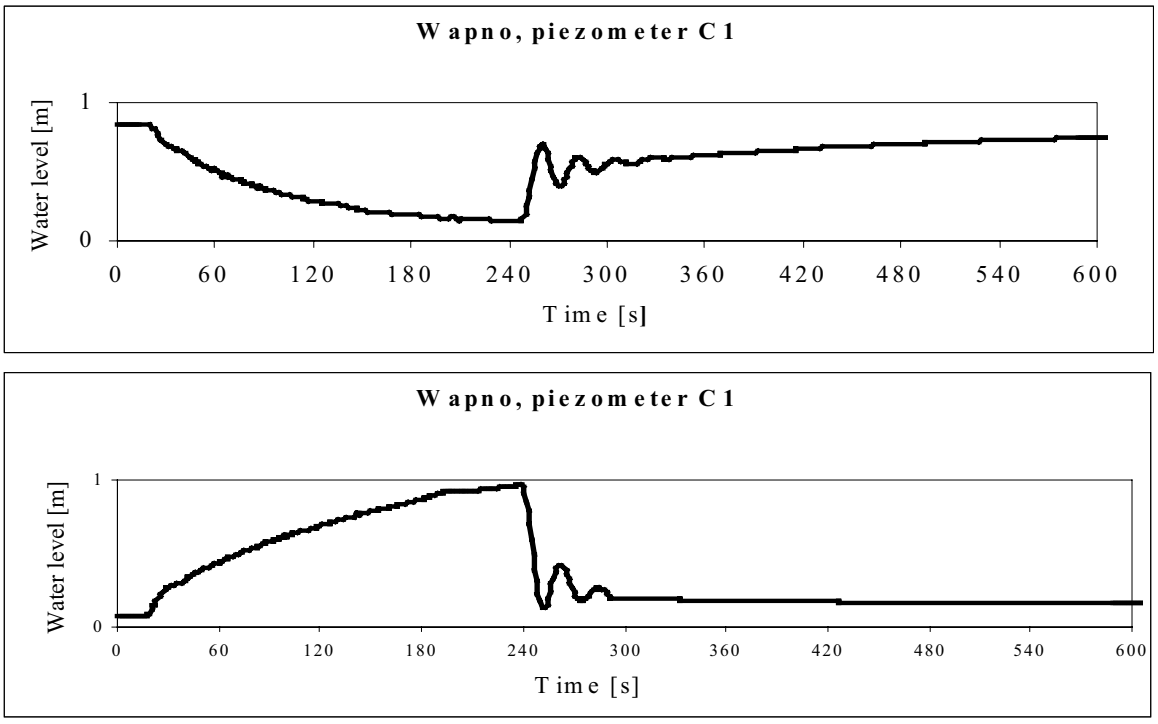

Figure 1. Water level motion in the C1 piezometer

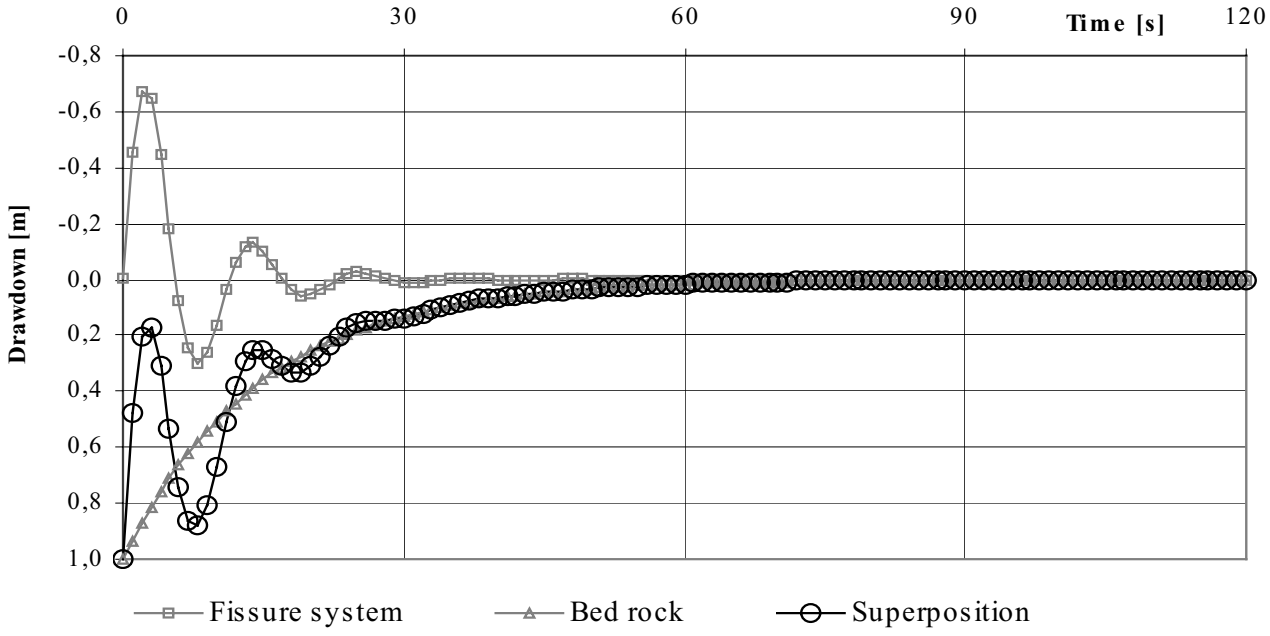

Figure 2. An example of separation of the water level motion into oscillatory and aperiodic components

piezometer through the system of fissures and fractures can be observed. In the final phase, permeability of the bed-rock came into play. The hydraulic conductivity coefficient of the fissure and fracture system can be computed on the basis of the damped oscillations part. The hydraulic conductivity coefficient of the bed-rock can be computed on the basis of the aperiodic part.

The interpretation should be started with separation of he recorded function $s = s(t)$ into the two components:

$$s(t) = s_{osc}(t) + s_{apr}(t) \tag{1}$$

The oscillatory component $s_{osc}(t)$ is described by the equation:

$$s_{osc}(t) = s_0 \exp(-\beta\omega_0 t)\sin\left[\omega_0\sqrt{1-\beta^2}\,(t-t_0)\right] \tag{2}$$

where: s_0 is the initial depression, β - the oscillation damping coefficient, ω_0 - the free oscillation frequency, t_0 - the starting moment of the free rise of the water level.

The aperiodic component s_{apr} is described by the exponential motion equation:

$$s_{apr}(t) = s_0 \exp\left(-\beta + \sqrt{\beta^2 - 1}\right)t = s_0 \exp(\gamma t) \tag{3}$$

where: γ is the exponent.

In case of air compression $s_{apr} = s_f - (s_f - s_0)\exp(\gamma t)$ and in case of air suction $s_{apr} = s_f + (s_0 - s_f)\exp(\gamma t)$. The exponent γ can be determined from the aperiodic part of the water level motion. The depressions s_0 and s_f are the initial and the fixed water level depression during the PARAMEX method examination respectively. The proposed methodology of interpretation is illustrated by fig.2.

In the example presented above the hydraulic conductivity coefficient of the fissure system was high in comparison with the bed-rock hydraulic conductivity coefficient. For this reason the components of the water level motion had a different character: oscillatory and aperiodic. Theoretically, it may be expected that a similar phenomenon of superposition of water level motions will occur when the fissure system and he bed-rock have filtration parameters of comparable magnitude. In such case both the initial and the final phases of the water level motion will have an aperiodic character with different values of the exponent γ. This case will be much more difficult to identify, because the separation of the recorded function $s = s(t)$ will require determination of the inflection point as well as the two aperiodic components with different values of he exponents γ_1 and γ_2.

EXAMPLE OF CALCULATING THE HYDRAULIC CONDUCTIVITY COEFFICIENT

On the basis of the recorded water level motion functions it was possible to compute the hydraulic conductivity coefficient for both the system of cavities and fissures and the bed-rock. The results are presented in Tab.1.

Table 1. Breakdown of the hydraulic conductivity coefficient values of fissure bodies of double permeability

		Hydraulic conductivity coefficient k [m/s]	
Piezometer	Location	Fissure system	Bed-rock
C1	Salt dome Wapno	$3{,}38\cdot10^{-4}$	$2{,}75\cdot10^{-6}$

The case discussed above, recorded during examination in the region of the salt dome in Wapno indicate new possibilities of application of the PARAMEX method for identification of hydrogeological parameters of fissure bodies with double hydraulic permeability.

REFERENCE

Fetter CW (1994) Applied hydrogeology. Prentice-Hall, Englewood Cliffs

Małoszewski P, Zuber A (1985) On the theory of tracers experiments in fissured rocks with a porous matrix. J Hydrology 79

Marciniak M (2001) Identification of hydraulic conductivity coefficient of aquifers using the PARAMEX test. {In}: Seiler KP, Wonhlich S (eds), New Approaches Characterizing Groundwater Flow, vol.2., XXXI Congress IAH, Munich

Streamtube model used to define anisotropic tensors describing tomographical three dimensional gas flow and transport within fracture networks at a laboratory benchscale

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A b s t r a c t : Three dimensional flow and transport in fractured porous rocks is commonly encountered in reality, but extremely difficult to model accurately. At a discrete laboratory small scale (typically of the order of 10cm) individual processes and parameters defining the physical conditions of single fractures may be well defined and modelled. However at a larger scale where fracture networks dominate the flow and transport characteristics, the interaction of the various processes controlling flow and transport in the fracture system coupled in some cases with a porous medium can not easily be defined. In this paper a model used to investigate the three dimensional flow systems in bench scale laboratory samples (sample diameter 30cm, length 40cm) containing fracture networks in porous material is presented. The model avoids the definition of the individual processes and concentrates on the integral flow and transport signal dependent on the geometry of the flow systems developed during gas tomographical flow and transport investigation. The use of the model to analyse the tomographical data allowed the definition of three dimensional anisotropic tensor defining the flow and transport characteristics of the fractured systems based on experimental results.

Describing the fractured porous system from a process perspective and simplifying the input parameters so that only the dominant mechanisms are represented gives an efficient method to determine the spatial variation in flow and transport in the samples. Here a process orientated multi-dimensional modelling approach has been developed which is used to analyse tomographical data from a variety of experimental investigation techniques at different scales. This method can also be applied to a number of real field scale investigation techniques.

McDermott *et al.* (2003a) present experimental equipment, the multiple input output jacket (MIOJ), for the tomographical investigation of highly fractured porous sandstone samples, fig.1. The recovery of these samples is discussed in McDermott *et al.* (2003b). This experimental cell allows the directional determination of flow and transport parameters for point to point measurements, surface to surface measurements, fracture to fracture measurements or a combination thereof.

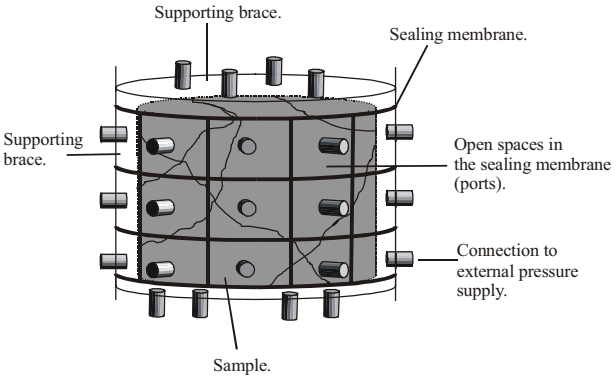

Figure 1. Multiple Input Output Jacket

Within the MIOJ there are three types of flow field, which combine to form the stable flow conditions encountered throughout the experimental series. These consist of what the authors term the one dimensional flow field where under steady state conditions the pressure head varies only in one dimension, the two dimensional flow field where under steady state conditions the pressure head varies in two dimensions and thirdly, the three dimensional flow field, where under steady state flow conditions the pressure head varies in three dimensions.

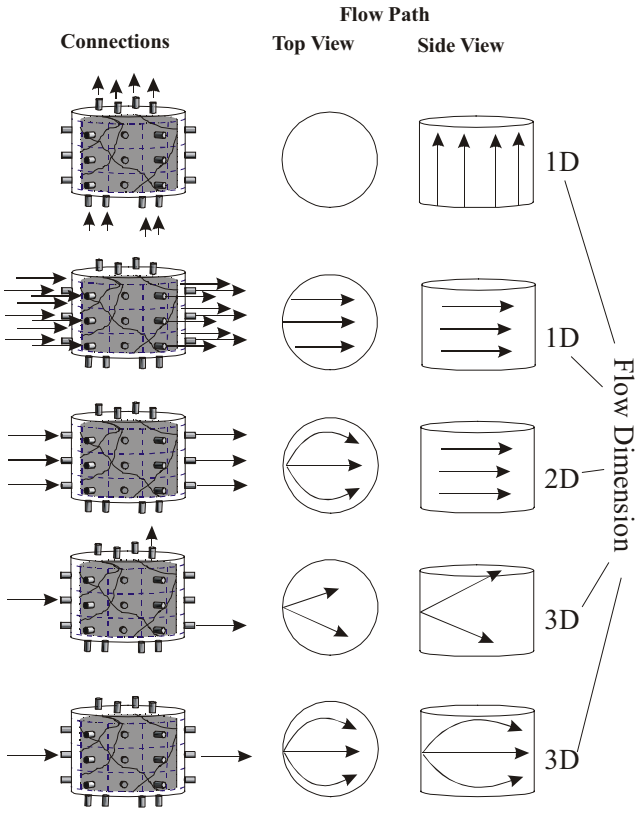

Figure 2. Flow Field Geometries within the MIOJ

These flow field geometries are not limited to the laboratory (see Datta-Gupta *et al.* 2002, Zlotnik and Ledder 1996; Heer and Hadermann 1994). For example the two dimensional flow field can be generated by some form of longitudinally continuous input and extraction across an aquifer such as two boreholes fully penetrating an aquifer, or in the case of the MIOJ a longitudinal injection coupled with longitudinal extraction across the cell. The three dimensional flow field could be generated by partial penetration of an aquifer by a two well system or a circulation well, in the case of the MIOJ a point injection and point extraction across the cell. The flow field geometries possible within the cell are presented in fig.2.

In McDermott *et al.* (2003a) the results of a simple one dimensional model for the initial interpretation of the experimental results is presented. However, as noted this is an oversimplification of the flow and transport signal which is in reality dependent on the three dimensional geometry of the system. In order to enable a more accurate determination of these parameters a three-dimensional stream tube model was developed (McDermott 1999) to provide a base upon which the experimental results could be compared. The principles behind this stream tube model are presented in fig.3. Here the stream tubes are defined by the geometry of the system and the boundary conditions, the flow and transport signal is then considered to be a combination of the various stream tubes.

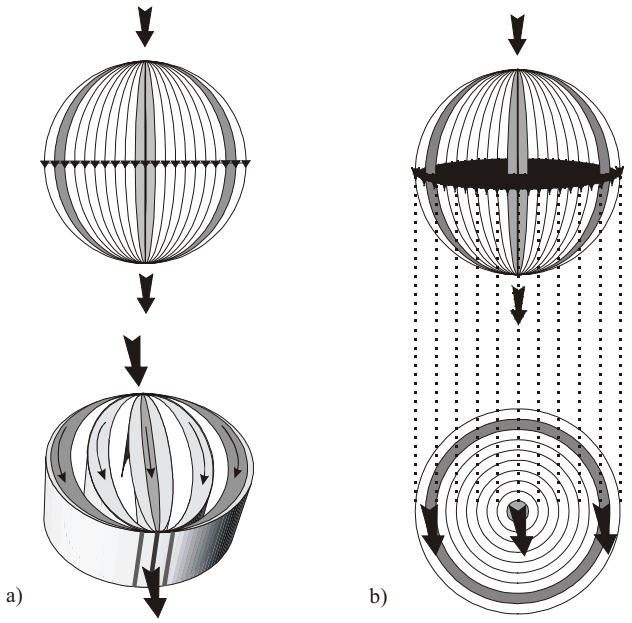

Figure 3. Stream tube model geometry based on the geometry of the flow field.
a) Two dimensional flow field
b) Three dimensional flow

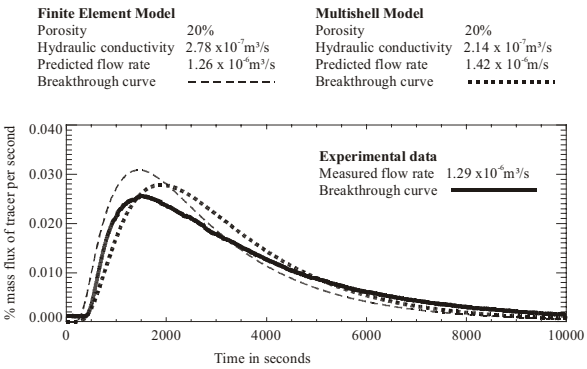

Figure 4. Comparison of measured data with model predictions by the stream tube model (multi-shell model) and a finite element mode

This assumption and modelling of the various perturbations in the system was compared with experimental results for flow and tracer transport (helium) in a simplified quasi homogeneous sample and with a finite element model of the system, fig.4. Once the basis for the comparison of the results was established, the model was used to analyse results from highly fractured samples to derive two and three dimensional flow and transport tensor fields, fig.5 and 6. These irregular tensor fields allow the prediction of the flow and transport behaviour at the scale of the sample being investigated and comparison of several different samples allows predictive modelling of the flow and transport behaviour of the system.

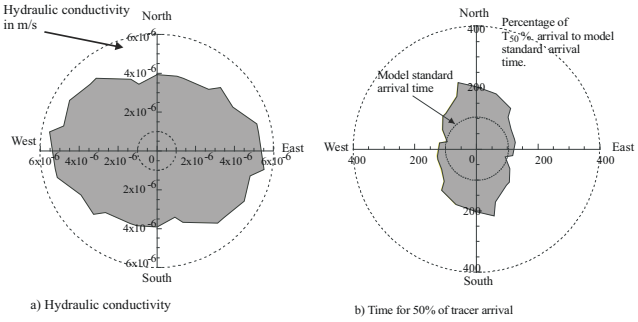

Figure 5. Example of a hydraulic and transport tensor field for a highly fractured porous sandstone (2D)

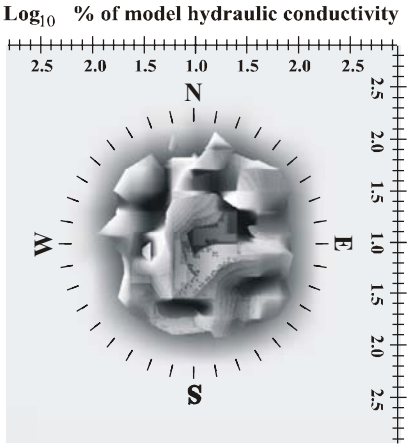

Figure 6. Example of a three dimensional irregular hydraulic conductivity distribution derived by comparison with the stream tube model prediction

REFERENCES

Datta-Gupta A, Yoon S, Vasco DW, Pope GA (2002) Inverse modelling of partitioning interwell tracer tests: A streamline approach. Water Resources Research 38(6):15-1

Heer W, Hadermann J (1994) Grimsel Test Site Modelling Radionuclide Migration Field Experiments, PSI-Bericht Nr 94-13

McDermott CI, Sauter M, Liedl R (2003a) New experimental techniques for pneumatic tomographical determination of the flow and transport parameters of highly fractured porous rock samples, Journal of Hydrology, accepted in print.

McDermott CI, Sinclair B, Sauter M (2003b) Recovery of undisturbed highly fractured bench scale samples (diameter 30cm x 35cm) for laboratory investigation, Engineering Geology 69(122):161-170

McDermott CI (1999) New Experimental and Modelling Techniques to Investigate the Fractured Porous System, Dissertation an der Geowissenschaftlichen Fakultät der Universität Tübingen, Germany, 170p

Zlotnik V, Ledder G (1996) Theory of dipole flow in uniform anisotropic aquifers, Water Resources Research 32(4):1119-1128

Instrumentation and methodology for the hydraulic characterization of fractured rocks

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A b s t r a c t : In recent years, the study of low-permeability geological formations, which include various types of fractured rocks, has undergone considerable development. Among other reasons, this is due to the utility of such materials, which act as a natural geological barrier surrounding the storage zone of different types of waste, preventing the water from bringing them into contact with the biosphere, and for the evaluation of groundwater resources that could constitute a supply of drinking water for small urban developments. In order to obtain the hydraulic characterization of such formations, it is necessary to develop a methodology together with specific instrumentation suited to the physical characteristics of these formations. For this purpose the Spanish Geological Survey has designed and built a Mobile Hydrogeological Characterization Unit for low permeability formations.

In recent years, the study of low-permeability geological formations has undergone considerable development because of its usefulness as a natural geological barrier surrounding the deposition or storage area for different types of materials, thus preventing water from bringing these into contact with the biosphere. Additionally, the growing demand for water resources has led to consider low-permeability materials, and in particular fractured formations, as a potential site of groundwater resources capable of solving the water supply problems of small urban areas or industrial plants.

Low-permeability formations can be defined as geological structures that do not store appreciable quantities of water or as ones that are only capable of transmitting it very slowly. Depending on their hydraulic conductivity they can be subdivided into the following classes:

- very low-permeability formations, with hydraulic conductivity values (k) of less than 1 x 10^{-12} m/s;
- low-permeability formations, with hydraulic conductivity values between 1 x 10^{-12} m/s and 1 x 10^{-9} m/s;
- slightly permeable formations, with values of 1 x 10^{-9} m/s to 1 x 10^{-7} m/s and, finally,
- moderately permeable formations, with values between 1 x 10^{-7} m/s and 1 x 10^{-5} m/s.

Due to the physical characteristics of low-permeability formations, do not usually enable to apply the techniques of hydraulic characterization traditionally applied to permeable formations, and so specific instrumentation must be developed.

Within the framework of a specific agreement with the National Radioactive Waste Management Agency (ENRESA, Spanish initials), and with the objective of carrying out hydrogeologic studies of this type of formations, the Spanish Geological Survey (IGME, Spanish initials) has designed and built a Mobile Hydrogeological Characterization Unit (UMH, Spanish initials) for low permeability formations, which has been operational since 1998.

The UMH comprises two 4-wheel drive trucks. The first of these, denominated the Base Vehicle, includes the data acquisition and interpretation system, the inflated packers system, the flow control injection system and the equipment of depth. It also incorporates an area for the assembling and maintenance of the UMH elements. These systems are located allowing, among others possibilities, to carry out injection tests with a range of flow rate between 0.0005 L/min to 40.3 L/min (Mejías *et al*. 1995); the inflated of the packers with Nitrogen or with water; the acquisition of pressure, temperature and rate data and the position of the equipment of depth in the test section to characterise. The effective compressibility value, obtained experimentally, for the standard equipment of depth used in the UMH was 2.78 x 10^{-8} Pa-1 (Martínez-Navarrete *et al*. 1995).

The second truck, the Descent Vehicle, is responsible for lowering the equipment of depth by means of a modified drilling rig, the location of the winches of the electrical cable and the inflated line of the packers, as well as transport of the pipes. Among other possibilities, the UMH allows the following test methods to be applied: transient injection tests at constant-rate of flow or at constant-pressure (Jacob and Lohman 1952), quasi-steady-state injection (Almen *et al*. 1986), pressure fall-off, slug test (Cooper *et al*. 1967) and pulse test (Bredehoeft *et al*. 1980). The objective of hydraulic testing is to determine the hydraulic parameters of the formation, the characterization of the fractures and to obtain the piezometric levels of the intervals tested (Almen *et al*. 1986). Hydraulic testing provides mean hydraulic conductivity values for the section being tested, which might be affected, in the surroundings of the borehole, by the drilling itself, by the construction characteristics of the borehole and by the effects of turbulent flow (Nagra 1989).

The characterization methodology may vary, depending on its objectives, on the type of formation, on the construction characteristics and availability of the borehole, on the prior information possessed and on the instrumentation used. The methodology of hydrogeological characterization that can be applied by the UMH to a research borehole in fractured rocks can be divided into two phases:

Overview phase: This basically consists of carrying out injection tests, in a quasi-steady-state, in sections with a length equivalent to about 5-10% of the total depth of the borehole. A double-packer device is used (fig.1), and the duration of this test is sufficient to obtain a quasi-steady-state for the injection phase, about 30-40 minutes, followed by a recovery period of similar duration. The hydraulic conductivity values obtained are not as precise as those achieved by other test methods, and may vary by up to one order of magnitude with respect to transient injection tests. Nevertheless, a fairly precise estimate is obtained of the behaviour of the formation in the vicinity of the tested area and of the distribution of permeabilities within the borehole, using relatively short test times.

In this initial phase, it is also useful to perform an injection test in a transient state and/or pulse test or slug test for the whole borehole, with a single-packer device, in order to obtain general information on the permeability of the borehole and which is valid as a benchmark for the results obtained in each of the sections. The recovery time for these whole borehole tests are usually acceptable for low-permeability formations, as they have higher transmissivity values due to the length of the test section.

Once this initial distribution of the hydraulic conductivity has been determined, and from the data compiled by the drilling cores and the geophysical logging concerning the location, orientation, density, length, aperture, roughness and filling of the unconformities and fractures, it is possible to proceed and establish the test sections to be tested during the second phase.

Detailed reconnaissance phase: In this phase, the test section is much shorter than in the previous; the lengths normally used

measure 1 m to 5 m, this section length being influenced by the size of the fractured area to be characterized and by the limitations imposed by the state of the borehole walls regarding to the correct sealing. In this phase, therefore, the tester seeks to achieve a balance between these two limitations, carrying out as many tests as possible with a single section length, thus avoiding the necessity of lowering and lifting up the equipment of depth within the borehole when the length of the test section is modified. Once the sections to be characterized in detail have been defined, and depending on the value of the hydraulic conductivity obtained in the first phase, the hydraulic tests are carried out. This testing is performed using a double-packer device and controlling the pressure in the sections above and below the test section, to ensure that the latter is isolated.

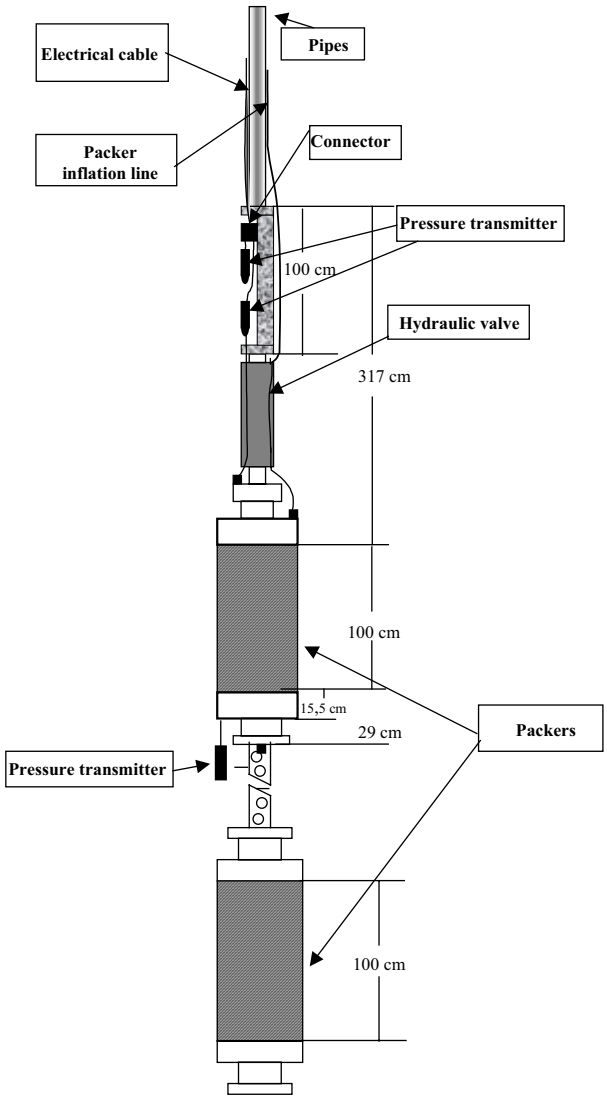

Figure 1. Double –packer device.

The general test sequence for a given section begins with an transient injection test at constant-pressure or at constant-rate. The former is normally preferred, as it avoids borehole storage effects since the down-hole pressure does not change during the test from the instant at which the rate variations begin to be measured, after the pressure has been stabilised. Moreover, in practice, it is more practical to effect very small variations in the flow rate in order to maintain a constant pressure. The duration of the injection period should be around 3 hours for it to affect a sufficient volume of the rock, and not only the closest areas as is the case when injection test in a quasi-steady-state or pulse or slug tests are applied. The volume of rock affected depends on the duration of the test and on the hydraulic parameters of the formation. For a greater volume of rock affected, the mean hydraulic conductivity value becomes more representative of the rock mass in the surroundings of the borehole, with the heterogeneities of the formation being included within an equivalent homogeneous and porous medium.

The instrumentation and methodology described above have been applied to various technical studies and commercial operations carried out by IGME.

The formations studied can be divided into two main groups: on the one hand, igneous, metamorphic and volcanic rocks, and on the other, non-consolidated sedimentary rocks. Although the basic instrumentation employed is the same for both types of formation, the specific characteristics of non-consolidated sedimentary lithologies require certain unique aspects of the test methodology to be used (López-Geta *et al*. 1994).

In the case of metamorphic and volcanic formations, the methodology was applied to shale and rhyolite lithologies, respectively, in order to evaluate the performance of the materials studied as a natural geological barrier between open pits (used to store mud, mining rock wastes and contact waters from mining activities) and detritic aquifers (Mejías *et al*. 2002).

REFERENCES

Almen KE, Andersson JE, Carlsson L, Hansson K, Larsson NA (1986) Hydraulic testing in crystalline rock. A comparative study of single-hole test methods. Technical Report, SKB, Uppsala:86-27, 183 pp

Bredehoeft JD, Papadopulos IS (1980) A method for determining the hydraulic properties of tight formations. Water Resources Research 16(1):233-238

Cooper HH, Bredehoeft JD, Papadopulos IS (1967) Response of a finite-diameter well to an instantaneous charge of water. Water Resources Research 3(1):263-269

Jacob CE, Lohman S (1952) Nonsteady flow to a well of constant drawdown in an extensive aquifer. Trans Am Geophys Union Ang, 559-569

López-Geta JA, Grima J, Martínez-Navarrete C (1994) Borehole testing and test interpretation in the San Pedro Clay Formation. In Workshop on determination of hydraulic and hydrochemical characteristics of Argillaceous rock, Nottingham, Session III, Hydraulic Testing, 195-211

Martínez-Navarrete C, Grima J, Mejías M, Gómez JA (1995) Celda de presión para ensayo de componentes de un equipo de testificación hidráulica. Especificaciones técnicas y ensayos. Hidrogeología y Recursos Hidráulicos 19:209-222

Mejías M, Grima J, Martínez-Navarrete C, Gómez JA (1995) Sistema de control de flujo para la realización de ensayos hidráulicos de inyección. Hidrogeología y Recursos Hidráulicos 19:223-236

Mejías M, López-Geta JA, Segura D (2002) Caracterización de formaciones de baja permeabilidad mediante ensayos hidráulicos: aplicación a dos sondeos de reconocimiento situados respectivamente al Sur y Este de las cortas mineras de Aznalcóllar y Los Frailes en la mina de Boliden-Apirsa, S.L. (Aznalcóllar, Sevilla). Boletín Geológico y Minero 113(1):45-55

Nagra (1989) Interpretation of hydraulic testing in crystalline rock at the Leuggern borehole. Technical Report, 87-19, Baden, 299 pp

3D characterisation of the micro-geometry changes of a single fracture in the course of dissolution

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A b s t r a c t : Carbonate dissolution of tensile fractures during percolation by CO_2-enriched fluid is studied using synchrotronic X-Ray Computed Micro Tomography as a tool to quantify the changes of the fracture walls geometry and extend. The experimental dissolution of a pure-calcite sample confirms the process of homogeneous chemical "erosion" classically implemented in the numerical simulators, but with a reactive surface coefficient much larger than unity. In opposition, the dissolution of a non-pure calcite sample, representative of the average micritic carbonate composition, displays very heterogeneous dissolution patterns associated with an increase of the fractal dimension. The initial topographic surfaces of the fracture walls evolve rapidly toward "non-topographic" interfaces displaying multiple overhangs due the preferential dissolution of the carbonate grains. In this case the classical 2D-profilometric methods fail. The specific surface coefficient increases strongly, more than 5 times the planar surface, and probably faster than the reactive surface.

INTRODUCTION

Limestone aquifers constitute a major reserve of fresh water throughout the world. The fractures, which are the principal path for water flow and potential pollution, can be strongly modified by geochemical transfers because of the high reactivity of the carbonates in continental environments. Experimental, modelling and theoretical studies of single fracture flow and transport put forward the strong control of the fracture aperture, surface roughness and aperture tortuosity (due either to twisting of the median plan or to the distribution of the contact points) on the flow and dispersion (Adler and Thovert 1999). Although theoretical basis exists (Lasaga 1998), it is only recently that quantitative modelling and experimental measurements of the fracture aperture spatial changes bound by chemical reactions were realized (Dijk and Berkowitz 1998), producing important constraints for modelling flow and dissolution patterns. However, large uncertainties still remain on the relation between the macroscopic evolution of the aperture and the microscopic (grain scale) morphological evolution. Furthermore, assuming that (i) flow and transport can be modelled using aperture and roughness as input parameters and (ii) thermodynamic and kinetic coefficients of reactions are known, the reaction-transport-coupled modelling of the aperture change requires the knowledge of the spatial and temporal evolution of the reactive surfaces. This parameter acts as a multiplicative coefficient of the rock-fluid transfers so that it is a key parameter, yet difficult to measure

The aim of this presentation is to report the results of reactive percolation experiments in a single fracture for which X-Ray computed tomography is used to determine the structural changes in fracture morphology in course of dissolution.

EXPERIMENTAL SETUP AND DATA ACQUISITION

The experiment focuses on the percolation of acidic fluid in tensile rough fissures sub-collinear to the core axis. The cores are 12mm long and 6 mm diameter. Dissolution is obtained by flowing, at a constant rate of 2.8 10^{-9} m^3/s, pure water enriched with carbon dioxide at partial pressure of 0.1 MPa ($pH = 4 \pm 0.1$). Output pH is 5.1 ± 0.15. As the mini-cores were rigidified with epoxy, the effect of confining pressure (equal to the max pressure at the inlet) variation was negligible. The pressure at the outlet was maintained above 0.1 MPa in order to avoid CO_2 degassing in the mini-core.

At the initial state and for different stages of dissolution, we record the sample structure using non invasive X-ray computed micro-tomography CMT. This technique is based on the X-ray attenuation measurements of thousand radiographies taken at different angles of the sample. We used the ID19 beam of European Synchrotron Radiation Facility which allows us to observe digital images of the evolution of the geometrical characteristics of the sample over four scales with a resolution of 4.91µm. Then, fracture walls are extracted from 2048 X 2048 x 2048 tri-dimensional images.

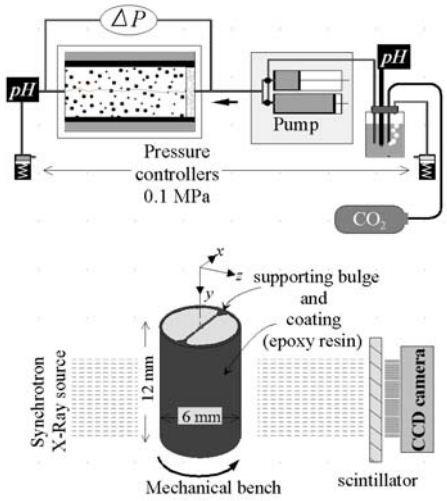

Figure 1. Schematic illustration of (top) the dissolution reactor, (bottom) the mini-core characteristics and the tomographic apparatus

RESUTS AND DISCUSSION

Two samples of micritic limestone of same origin are studied. The first one is a pure calcite (ϕ = 2.2 %) with a fracture of aperture a = 50 ± 8 µm and the second is composed of 85 w% calcite, 10 w% dolomite, 5 w% clay (ϕ = 5.6 %) with a fracture of 20 ± 7 µm. For both samples, the initial fracture surfaces are topographic surfaces (TS), that is, to any x-y coordinate corresponds a single elevation z. In this case fracture walls can be analyzed by extracting the x-y projection of the CMT images, producing profilometry-equivalent data set to be characterized by classical statistical and spectral surface analysis. Results display ubiquitous self-affine behaviour all over the measured scale range, from 5µm to 1cm. The fractal dimension D, computed coherently using 1D and 2D (Fourier Transform) power spectrum method is 2.5 ± 0.1 without noticeable anisotropy for both the samples. At the initial stage, the reactive surface coefficient S_R is

estimated as the product of the volume fraction of the mineral involved in the calcite reaction (1 for sample 1 and .85 for sample 2), by the specific surface coefficient S_S. The later is the ratio of the total surface of the fracture walls to its planar projection, so that $S_S = 1$ for a planar surface. It is assumed here that the fracture intersects the rock randomly. Usually, for numerical modelling, S_R is kept constant and S_S is embedded in an "efficient" kinetic reaction rate (Lasaga 1998) which doesn't take into account S_R and S_S changes during dissolution. The total surface of each of the fracture walls is computed from the CMT images by:

$$S_z = \iint_{x,y} \sqrt{\left(\frac{\partial z}{\partial x}\right)^2 + \left(\frac{\partial z}{\partial y}\right)^2 + 1} \; dxdy$$

were $z(x,y)$ are the fracture wall elevations.
The dissolution of the 100% carbonate sample is characterised by a uniform translation of the fractures walls surfaces along the z axis. As a consequence, the fractal dimension D, the specific surface and reactive surface coefficients (fig.3) are all invariant. The fracture walls remain TS.

Figure 2. A cross-section of the fracture. From left to right: (1) 100% carbonate before dissolution, (2) 100% carbonate after dissolution, (3) 85% carbonate before dissolution, (4) 85% carbonate after dissolution

In contrast, the dissolution of the second sample is noticeably heterogeneous (fig.2). The fracture walls cannot be described as TS anymore; the surfaces are folded with multiple overhangs. An analysis of 2D-projected digital images of the fracture walls would be biased. The surfaces were then analysed using isomorphic 2D and 3D-box-counting method (BCM). All those methods give similar results: a linear relation between the logarithm of the number of boxes of dimension l and the logarithm of l. This indicates that the self-affine fractal characteristic of the surface remains. A theoretical value of the fractal dimension of the surfaces can be calculated from the slope s of the former linear trend. A value of $D_{BCM} = 2.2 \pm 0.1$ was calculated for the fracture surfaces at the initial stage. Dissolution induces an increases toward $D_{BCM} = 2.4 \pm 0.1$ for the final stage of dissolution. Albeit the noticeable, but expected (Schmittbuhl *et al*. 1995), difference between the dimension measured by spectral methods and the BCM, the results reveal a quantifiable increase of the fractal dimension. As shown on fig.3, the dissolution is also characterised by a large increase of the specific surface coefficient (from 1.5 to more than 4.5) together with a noticeable decorrelation between the aperture a and S_S as dissolution increases. This data spreading is to be related with the increasing chemical and structural heterogeneity of the fracture walls while dissolution progresses.

CONCLUSIONS

- The remarkable performances of the synchrotronic X-ray CMT (compared to diverging source X-ray methods and NMRI) has proved to be an efficient toolsto quantify the fracture surface changes bounded by dissolution, with a resolution close to the grain size and over a large field of view (2048^3 voxels or four measurement scales). It is presently the leading method for monitoring dynamic processes at this scale.
- The dissolution of a monophasic carbonate is characterised by a process of chemical erosion. The properties of the surface are preserved. Though, it must be noticed that the reactive surface coefficient, here equal to the specific surface coefficient, is certainly much larger than 1. We found that with a resolution limit of 4.91 m, S_S is close to 1.5 and that the fracture surfaces were self-affine fractal all over four orders of measurement. By definition the specific surface coefficient Ss is proportional to $(\lambda_C)^{2-D}$, then, if we assume that this characteristic persists until the average grain size of characteristic length $\lambda = 2\mu m$ (evaluated from SEM observations) one obtain a value of $S_S = 2.4$.

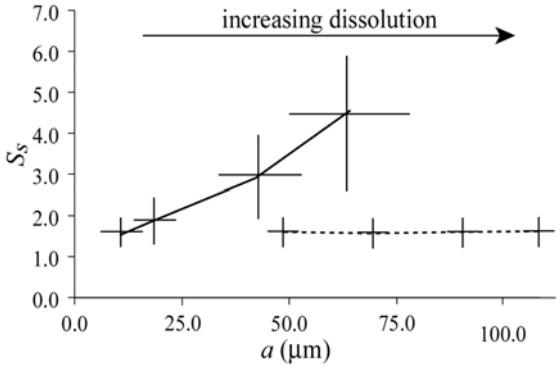

Figure 3. Specific surface as a function of the aperture. Plain and dashed curves correspond to the 85% and the 100% carbonate samples respectively. Crosses denote the data dispersion

- The dissolution of the non-pure carbonate sample displays deeply different behaviour characterised by a very heterogeneous dissolution leading to the creation of non topographic surfaces. In this case, profilometry methods fail to capture the real structures and the extension of the surfaces which is proved here to increase strongly. Using the same relation as above, one can estimate that a value of S_S larger than 9 is reached at the end of the dissolution experiment. However, because of the high heterogeneity of the dissolution, it is difficult to relate S_R to S_S which is certainly non-linear because of the preferential dissolution of the carbonated phase. The ubiquitous increase of S_S with a cannot persist indefinitely. From now it is important to consider dissolution over larger time in order to explore if this relation reaches an asymptotic regime or if cyclic behaviour takes place.

Acknowledgements: Many thanks to. ESRF-ID19 Team. Research partly funded by the European Commission-RDG-(EVK1-CT-2001-00091 "ALIANCE").

REFERENCES

Adler PM, Thovert JF (1999) Fractures and fractures networks. Kluwer Academic Publishers, The Netherlands

Dijk PE, Berkowitz B (1998) Precipitation and dissolution of reactive solutes in fractures. Water Resour Res 34(3):457-470

Lasaga AC (1998) Kinetic theory in the earth sciences. Princeton University Press, New Jersey

Schmittbuhl J, Vilotte JP, Roux S (1995) Reliability of self-affine measurements. Phys Rev, E 51, 131-147

New approaches towards an integrated model-based understanding of groundwater flow in fractured-aquifer catchments and implications for practical problems

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A b s t r a c t : Hydraulic properties of fractured aquifers at a regional scale are difficult to obtain, as usually a large number of observation wells and pumping tests (and also large amounts of money) are needed. Due to the usually large distances between observation wells, hydraulic properties can often only be gained from drawdown measurements at the pumping well. Especially storage properties obtained from these data are usually highly uncertain. Another problem is the regionalisation or upscaling of local hydraulic data. Analysis of transient discharge data in small rivers can be used to obtain mean hydraulic properties of different hard rocks at a regional scale. Basic problems (groundwater runoff separation, evapotranspiration losses from the saturated zone), their solution and a practical application are presented in this paper.

PROBLEM DESCRIPTION

The storage-discharge behaviour of fractured aquifers is not fully understood yet. Often a reliable model calibration of fractured aquifers is not possible, as only incomplete information is available (groundwater heads or discharge data, but not both). On the other hand it is important to know the hydraulic function (storage/discharge and head-gradient/discharge behaviour) of fractured aquifers, especially when dealing with questions like groundwater vulnerability.

Small catchments in the low mountain range of middle Europe are ideal areas for analysing groundwater flow in fractured systems. If the outflow from these aquifers feeds small rivers and both surface and groundwater catchment areas are more or less identically, the measured discharge and quality allows for analysing the entire water budget. If the subsurface catchment area is known, these aquifers can be considered as more or less closed systems. Analysing transient groundwater discharge into the river, important data can be obtained for the calibration of both SVAT-models (transient recharge calculation from climatic, vegetation, soil and rainfall data) and groundwater flow models.

Since input and output of the system are known, model calibration reduces, at the first glance, to the simple problem of describing the transformation from input to output. Using standard assumptions often made when dealing with discharge data, lead to an insufficient description of the system. The resulting values of discharge in the aquifer and its hydraulic properties can be completely wrong. This is demonstrated using data and model results of some small fractured shale catchments (catchment area below 100 km²) in Eastern Thuringia (Germany).

PREPARATION OF DISCHARGE DATA

Discharge data in rivers are usually composed of surface-water and groundwater components. To prepare measured discharge data for the analysis of aquifers hydraulic properties, groundwater runoff must be separated from the measured discharge. This can be done using graphical recession analysis or tracer studies. An objective separation can only be done, when using the results of tracer studies, as in fractured aquifers often fast groundwater components exists, which will probably be neglected when using graphical separation methods.

Differences in measured recession data between summer and winter are usually explained with areal evapotranspiration in the catchment. Analysing measured daily discharge fluctuations it can be pointed out, that in the low mountain range evapotranspiration losses from the saturated zone are limited to the valley area. For this reason, measured discharge data can be significant smaller than the catchments groundwater recharge. This will lead to errors when using summers recession curves for transient model calibration without taking into account evapotranspiration losses. A practical way to determine mean monthly evapotranspiration losses is to use mean monthly potential evapotranspiration values in the area, where the depth to water table is within root depth and capillary fringe.

The impact of the correction methods on mean groundwater recharge is shown in Tab.1. As standard method for mean recharge determination in the low mountain range in Germany Wundt's method is used. According to this simple method, mean groundwater recharge equals the mean of the lowest daily discharge values within each month of measured discharge for 10 years, at least.

Table 1. Mean groundwater recharge obtained from discharge analysis

Method	Mean groundwater recharge [mm/year]
Standard (Wundt)	80
Corrected for evapotranspiration	180
Corrected for evapotranspiration and fast groundwater runoff	220

To obtain transient recharge data as input for the transient groundwater-flow model, a transient recharge calculation using a SVAT-model (soil-vegetation-atmosphere-transfer) is needed. This model, which should be able to deal with fast recharge components (macropore flow), can be calibrated using the results of the discharge analysis.

HYDRAULIC PROPERTIES OF FRACTURED AQUIFERS

Transient discharge from an aquifer is mainly controlled by its void system. Fractured aquifers react with different hydraulic diffusivities over time, a feature which was first described by Barenblatt *et al.* (1960) by introducing the concept of multy-porosity or multy-continuum models.

According to De Swaan (1976) four hydraulic properties are needed to describe the transient behaviour of these systems:

Transmissivity A lateral flow through a fracture network only takes place within a small portion of the void system, called here the discharge fraction. The transmissivity of the discharge fraction can be determined by steady state model calibration using mean groundwater recharge and mean observed groundwater heads. The lateral flow through the system takes only place within the discharge fraction. For this reason it is assumed, that hydraulic conductivity within the discharge fraction remains constant over time.

Storage capacity of the discharge fraction During recharge events, fast flow components occur within the discharge fraction. High flow velocities within this system results from small storage capacities and hydraulic diffusivities.

Storage capacity of the complete system After some time, the system reacts with the hydraulic diffusivity of the complete system (storage capacity of the discharge and the storage fraction of the fracture network).

Resistance between discharge and storage fraction If and after what time a transition between recession with the hydraulic diffusivity of the discharge fraction and the complete system occurs, is a question of the resistance between discharge and storage fraction.

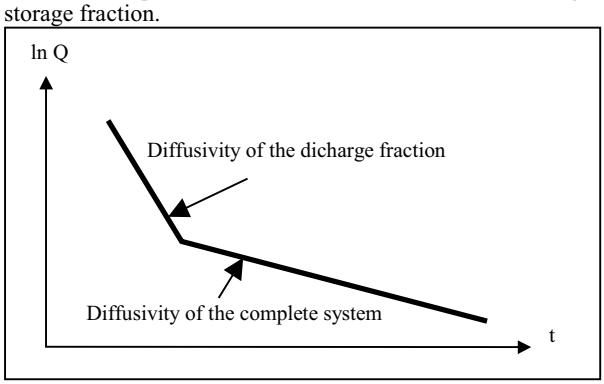

Figure 1. Typical groundwater discharge recession curve of a fractured, not karstified aquifer

A typical recession curve of a fractured aquifer is characterised by two or more linear segments (fig.1). Often the Maillet-formula is used to determine the recession constants for the different segments.

If the storage capacity of the total system was determined (e.g. by using a „standard" single continuum groundwater flow model), the storage capacity of the discharge fraction can be calculated from the ratio of the recession constants and the storage capacity of the total system (Probst 2002). The storage capacity of the storage system can be calculated easily by subtracting the storage capacities of the total system and the discharge fraction.

Standard single-continuum models were used to determine the mean hydraulic parameters shown in tab.2. Depth of the aquifer (weathered zone) was determined from several pumping tests and literature values to 20 m. Mean recharge was set to 220 mm/a. Note that only about 14 % of the hydraulically active void system build the discharge fraction.

Using some simple formulas, the hydraulic data can be transformed to an equivalent system of two orthogonal sets of parallel fractures. The mean distance between the fractures is calculated to 0.7 to 0.8 m, the mean fracture aperture is 256 µm. Both values are in good agreement with literature data.

Table 2. Mean hydraulic parameters of the fractured aquifer

Parameter	Value
Conductivity discharge fraction	$1.4*10^{-5}$ m/s
Storage Capacity total system	0.5 %
Storage Capacity, discharge fraction	0.068 %
Storage Capacity, storage fraction	0.432 %

Using measured discharge data without the corrections explained above, recharge is underestimated by a factor of 2 to 3. Note that the correction factor is a function of catchment size, recharge, climatic conditions and area with evapotranspiration losses from the saturated zone. When using this mean recharge as input for mean transmissivity calculations, it will also be underestimated by the same factor. As the transient behaviour of the aquifer is described by its hydraulic diffusivity, errors in transmissivity leads to a further error when determining the storage capacities from aquifers transient behaviour.

USE OF SINGLE CONTINUUM MODELS FOR TRANSIENT FLOW AND TRANSPORT IN FRACTURED AQUIFERS

Many complex models have been developed for describing transient groundwater flow in fractured aquifers. At a regional scale it is sufficient to describe the typical transient system behaviour. To do so, discharge and storage fraction must be separated within the model, a feature which is also possible when using single continuum models and the following assumptions.

The model grid is defined using storage and discharge elements (fig.2). If preferred flow directions exist, the model grid should be rotated accordingly.

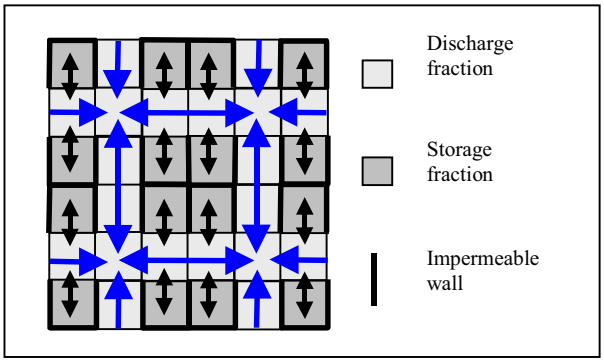

Figure 2. Grid design for a fractured, not karstified aquifer

Equivalent hydraulic properties for the groundwater flow model can be easily calculated using the model geometry and the hydraulic properties determined above.

During transient calibration, the resistance between discharge and storage fraction is determined. The resistance, which can be considered as hydraulic conductivity of the storage fraction is determined to 2.5 to $5*10^{-11}$ m/s. This value is about 25 to 50 times higher than conductivity values expected for an unfractured shale. It seems that most parts of the storage fraction are build from small fractures.

Using the hydraulic properties determined above, calculated transient discharge is in good agreement with measured values.

RESULTS

Effective hydraulic parameters of fractured aquifers can be determined with the discharge analysis presented here. These data are extremely helpful for regionalisation to areas, where detailed information is not available. They can be used for a wide field of practical questions, e.g. water budgets, discharge prediction (low flow) or vulnerability of an aquifer.

The method can also be used for advanced topics like karstified aquifers, coupled surface water-groundwater models or local models. For detailed flow models it is important to correlate transmissivity with the storage capacities of the system.

REFERENCES

Barenblatt G, Kochina I, Zheltov I (1960) Basic concepts on the theory of homogeneous liquids in fissured rocks. J Appl Math Mech 20:852-864

De Swann A (1976) Analytical solutions for determining naturally fractured reservoir properties by well testing. J Soc Petrol Eng 261:217-222

Probst M (2002) Der Einfluss des Grundwasserhaushaltes auf das Abflussverhalten kleiner Einzugsgebiete im Festgesteinsbereich der Mittelgebirge, Universität Kaiserslautern 2002

Large displacement slug tests

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A b s t r a c t : When conducting pneumatic slug tests in a fractured bedrock formation, the Initial Displacement (Ho) was increased upwards of 15m. The results indicate that the normalized head-time data was Ho dependent. Water level variations due to Large Displacement Slug Tests (LDST) were recorded at wells located up to 75m from the stressed well, allowing their use as monitoring wells for estimation of the formation storativity. LDST promises to be a valuable method for identifying hydraulic connections in heterogeneous formations.

Large Displacement Slug Tests (LDST) were defined as those with an Initial Displacement (Ho) larger than conventional values recommended in the literature (i.e., Ho < 1m). More than 200 pneumatic Slug Tests (ST) were conducted as part of an intensive hydraulic characterization program on a metamorphic fractured bedrock formation contaminated with chlorinated solvents. The program included more than 200 ST, more than 100 LDST with Ho up to 15m, and more than 20 Pumping Tests (PT) (Pulido–Silva *et al.* 2003a).

Straddle packers were used in five fractured-bedrock wells, to isolate discrete fracture zones within each well. High frequency logging pressure transducers (8 readings per second) were located within each isolated zone. Pressure transducers were also installed in nearby Monitoring Wells (MW) located up to 100 m from the Stressed Well (SW). Rising ST (RST) were conducted by pressurizing the isolated zone with nitrogen gas, waiting until water-pressure stabilization, and then initiating the ST by releasing pressure with a quick-opening valve (Butler 1998) Falling ST (FST) were performed by using a vacuum pump instead of nitrogen gas. After repeatability tests confirmed equivalent results with RST and FST for a given Ho, RST were preferred because they produced the near instantaneous Ho condition required by all ST analysis methods, regardless the Ho value (Fig.1).

Contrary to the usual assumption that the ST Normalized Head – Time Curve (NHTC) must be independent of Ho (McElwee 2002), it was systematically observed that for this fractured formation, NHTC continually displaced towards increasing time as Ho increased (Fig.2).

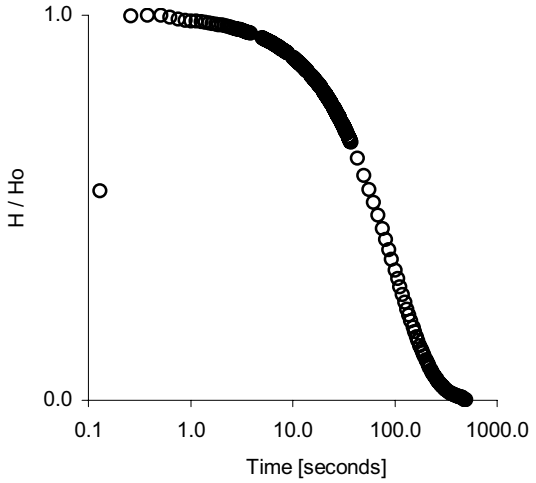

Figure 1. Typical LDST field data (well BBC3;Ho=3.92 m; isolated depth 30.35 - 34.75 m)

LDST caused significant water level variations at MW located as much as 75 m from SW, providing a valuable tool in the assessment of hydraulic connectivity between wells (Fig.3).

Besides the Cooper and Hvorslev methods, LDST were analyzed by the Finite-Difference and Finite-Element models in the HyTests software (Pulido–Silva *et al.* 2003b). These numerical models provided explanation for the NHTC

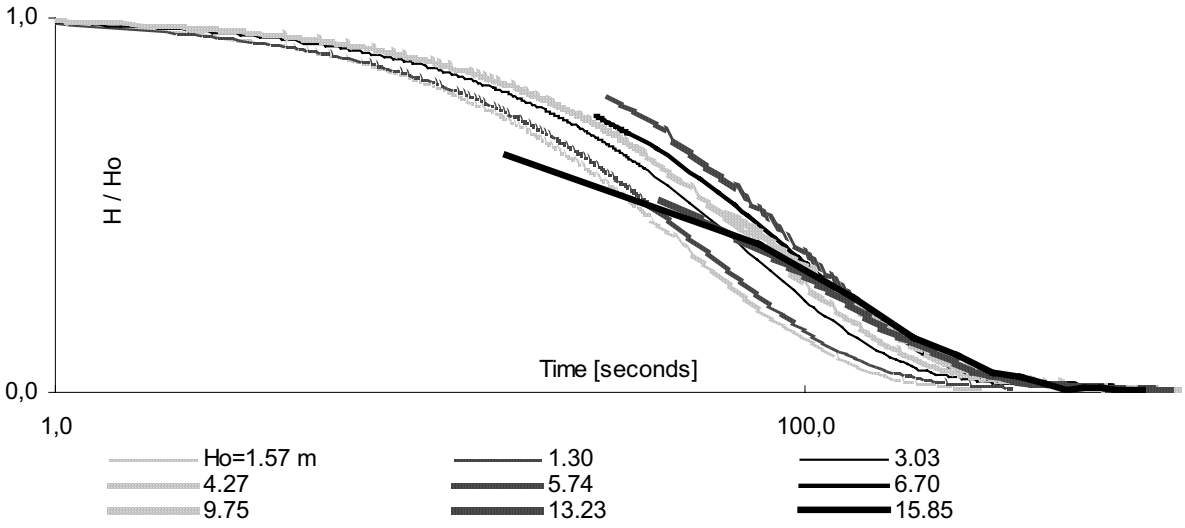

Figure 2. NHTC dependence with Ho (Well BBC4; isolated depth 46.1 – 47.8 m)

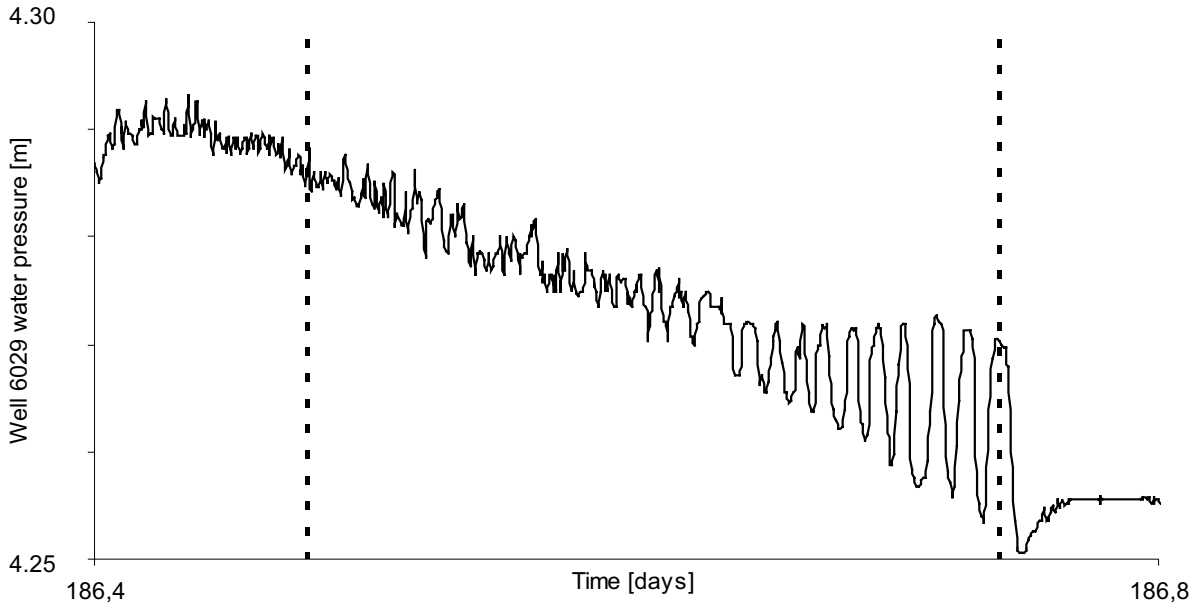

Figure 3. LDST responses at MW (30 LDST conducted at well BBC3 between the bracketed time interval with Ho from 0.36 m to 15.0 m; open borehole MW 6029 located 63 m from BBC3)

dependence with Ho, and estimated Storativity values by using the MW responses data. This then demonstrated the applicability of LDST to estimate not only hydraulic conductivity, but also storage coefficient. Finally, by using the Fractures-Network model provided by HyTests, LDST provided a method for identifying the spatial disposition of hydraulically-active fractures.

REFERENCES

Butler JJ (1998) The design, performance, and analysis of slug tests, 1st edition. Lewis, Boca Raton, 252 pp

McElwee CD (2002) Improving the analysis of slug tests. Journal of Hydrology 269: 122-133

Pulido–Silva G, Ballestero TP, Barrera MI, Marbet HJ, Kinner NE (2003a) Developing a conceptual hydrogeological model for a fractured bedrock formation. In: IAH International Conference on Groundwater In Fractured Rocks–Proc

Pulido–Silva G, Ballestero TP, Kinner NE (2003b) HyTests: a set of numerical models for hydrogeologic parameters estimation. In: IAH International Conference on Groundwater In Fractured Rocks–Proc

Remote sensing and geophysical applications for identification of deep seated potential aquifers in Precambrian crystalline formation: case study in Bellary district - Karnataka, India

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Lineaments deciphered from the Satellite imageries coupled with resistivity measurements facilitate proper location for construction of successful bore wells in hard-rock terrain. Encouraging results have been obtained by Central Ground Water Board, South Western Region by employing such techniques in the exploratory well programme.

Bellary district in Karnataka covers a total area of 8420 sq.km covering seven taluks is bounded by north latitude of $14^0$30' - $15^0$47' and east longitude of $75^0$45'-$77^0$11'. Physiographically the area is occupied by hills in the central part with plains in the east and west.

The district is mainly covered by Precambrian rock formations such as schists, granites and gneisses. Schists are mainly hornblende schists associated with phyllites and quartzite having NNW-SSE strike with a steep easterly dip of 70 to 85^0. Granites occurring in the district form the northern extension of Closepet granite and contain both pink and grey porphyritic varieties. Gneisses have assemblage of migmatite biotite gneiss and granitic gneiss, intruded often by acidic and basic veins. Gneisses show general trend of NNE-SSW to N-S with easterly dip of 60-70^0. In general N-S to NNW lineaments are coinciding with possible major fracture zones. However NE-SW lineaments are not uncommon in the district

Geomorphologically the area can be grouped into different land forms: i) Schists in general occurs at higher elevation is grouped as structural hills, ii) Granites occurring as main hillocks are grouped with the residual hills, iii) Dykes occurring in the district are grouped into linear ridges, iv) Pediment occurs as a small patch surrounding the residual hills of granite in the district and v) The remaining areas that are plain in nature are grouped into pediplain in the district. In the crystalline formations, characteristics of the rocks control the occurrence of groundwater. As these formations lack primary porosity, the degree of weathering and fracturing are important factors controlling their properties as aquifers. Groundwater occurs under phreatic and semi-confined conditions in the weathered and fractured rocks (fig.1).

Detailed hydrogeological survey is carried out in the area where exploratory tube well is required to be drilled. Care is also taken to see that bore well is located in the proximity of the village, so that after construction the well is utilized for drinking water needs of the villages. As a part of the hydrogeological investigation, the satellite imageries were studied to interpret lineaments where it is likely that deep-seated weathered and fractured zones exist forming potential aquifers. Supplementing to this, geophysical survey was also carried out on the lineaments and intersection of lineaments for confirmation of fracture zones. A typical electrical sounding curve is shown in fig.2. Drilling of the bore well is under taken on the pinpointed sites.

After the successful completion of the well, long duration pumping tests were conducted together with observation wells where the yields of the wells were more than 3 L/s.The analysis of the aquifer performance test is shown in fig.3a and 3b.

A total of 18 exploratory bore wells were drilled in the district out of which, 10 sites were pinpointed in the vicinity of lineaments followed by geophysical surveys.

After the compilation of the necessary information from the exploration the following inference is drawn. The Phreatic zone encountered between 15 and 51 m bgl. is delineated as a low potential zone. For most of the dug wells and shallow bore wells constructed in the district are either dry or low yielding wells. However, the exploratory bore wells drilled beyond 100m drilled in the district have brought out encouraging results. Out of 18 wells constructed, 60% have yielded more than 3 L/s, 28% have yielded 1 to 3 L/s and the remaining 12% have yielded less than 1 L/s. In general, maximum depths of the deep-seated fractures have been encountered up to a depth of 185 m bgl. In schist, granite and gneissic formations, the deep seated fractures were encountered with in a depth varying from 167, 187 and 141 m bgl., respectively.

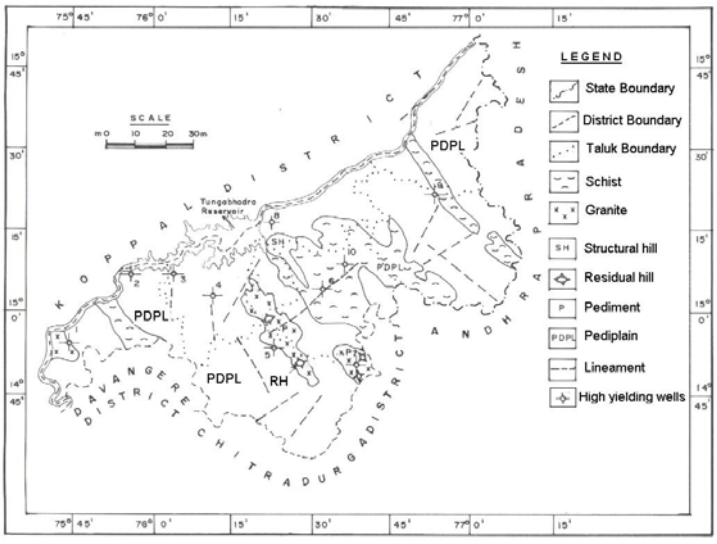

Figure 1. Location map of exploratory wells drilled in Bellary district

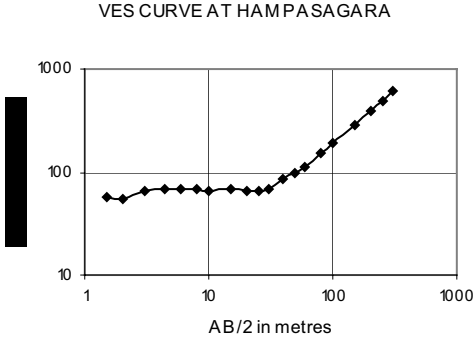

Figure 2. A typical electrical sounding curve

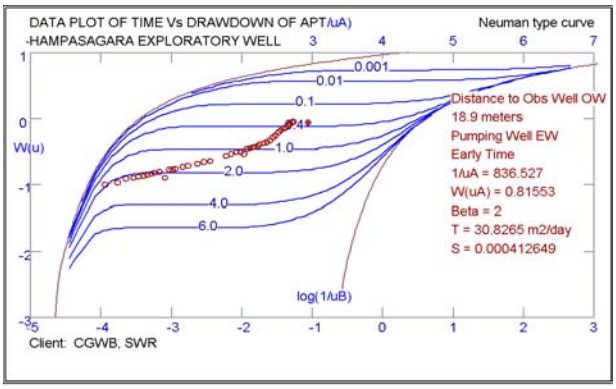

Figure 3a. Early time analysis of aquifer performance test

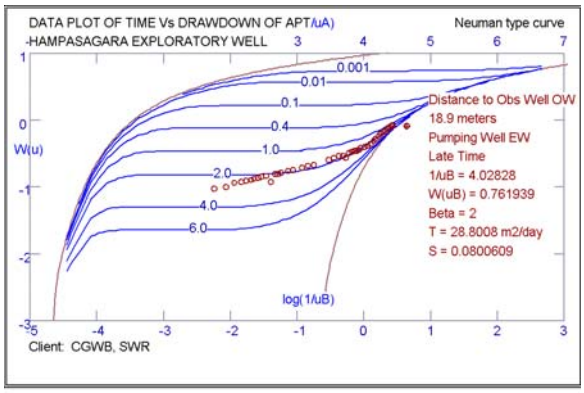

Figure 3b. Late time analysis of aquifer performance test

A comparative statement for the select high yielding wells drilled on lineaments in different hydrogeological environment is shown in tab.1.

It is seen from the table that the interpretation of the satellite data in addition to geophysical survey has contributed substantially in the location of successful bore wells.

The nature of groundwater flow system in hard-rock aquifers is not homogeneous. Hence test data results of exploratory wells are not comparable with each other. The data results obtained in various crystalline aquifers occurring in the district is presented in tab.2.

The test data inferred above has clearly shown that the wells drilled on the lineament proved to give sustainable yield in the drought prone area like Bellary district in Karnataka for formulating rural drinking water schemes.

Table 1. Salient hydrogeological data of exploratory bore wells drilled on the lineament in different hydrogelogical environment in Bellary district.

SL. no	Geology	Depth drilled Range in (m)	Casing depth Range (m)	Depth range ofFractures encountered (m)	Geophysical data interpretation in respect of the depth range of fracture(m)
1	Granite	144-200	10-15	46-48, 58-60, 91-92,102-103, 125-126,159-160, 180-181	40 -150
2	Gneiss	135-200	12-19	12-13, 15-16, 21-22,25-26, 28-29, 55-56,86-87, 123-124,128-129, 131-132,146-147	12-100
3	Schist	144-200	5-20	16-18, 20-21, 39-40,48-50, 56-57, 66-67,83-84, 91-92, 109-110,112-113, 116-117,149-150, 159-160,166-167	8 -135

Table2: Comparative pumping test data results of various crystalline aquifers of exploratory bore wells drilled based on lineaments in Bellary district

Sl.No	Type of aquifer	Discharge range in (L/s)	Draw down range in (m)	Specific Capacity range in (m)	Transmissivity range in (m)	Storativity range in (m)
1	Granite	4-4.2	15-16	22-24	188-358	$2.29x10^{-3}$
2	Gneiss	5.5-12	3-9	89-151	55-754	$1.32x10^{-2}$ -$8.44x10^{-4}$
3	Schist	4-13	6-12	41-178	57-227	$1.13x10^{-1}$ $4x10^{-4}$

Optimisation of aquifer parameters in the fractured rock aquifer system using numerical groundwater model

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The formation constants of aquifer such as transmissivity and storage coefficients are generally obtained from pumping tests by matching the draw down observation to one of the available analytical models. In the hard rock fractured aquifer system, the proper choice of suitable model is particularly a difficult phase of the study. The alternative method that may be used in the parameter estimation, namely the use of numerical model for repeated computations to optimize the parameters by minimizing the difference between the observed and predicted draw downs. In the crystalline formation the degree of weathering and fracturing of the litho-units are controlled by numerous factors such as topography, climate, texture, mineralogical composition and structural history. The characteristics of these rocks control the occurrence and movement of groundwater in hard rock. As these rocks lack primary porosity the degree of weathering and fracturing are important factors controlling their properties as aquifers. Groundwater occurs in these rocks under phreatic conditions in the weathered zone and under semi confined to confined conditions in the fractured portion at depth.

As a part of groundwater exploration in the hard rock terrain of Pudukottai district of Tamilnadu an exploratory well was drilled at Meyvazhisalai village (Fig.1).

The area is underlain by granitic gneisses. The well is located on the intersection of two lineaments identified based on the interpretation from the satellite imageries. Three observation wells were also drilled at suitable location to facilitate the estimation of directional transmissivities and storage coefficients of the aquifers. The main well was pumped at a constant rate of 6.2 L/s for 1000 minutes. The digital water level recorders were installed on all the three observation wells to monitor drawdown. The drawdown measurements are recorded at the rate of 0.3 seconds for the first 6 seconds. After this, it followed the logarithmic time interval and kept on increasing the interval between each sample until it reached user specified 30 minutes time interval. Then it entered into linear mode and recorded the readings at a time interval of 30 minutes.

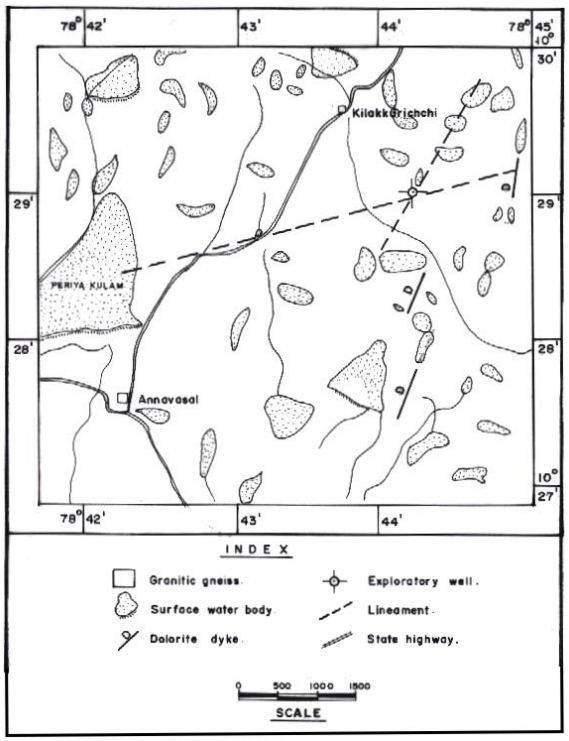

Figure 1. Exploratory well location map of Meyvazhisalai in Tamilnadu

Using the data generated from the digital water level recorder, analytical solution for the aquifer parameters was obtained by drawing the plot of time Vs. drawdown in double log paper (Fig.2). The values of transmissivity and storage coefficient derived from the plot were 9.878 m^2/d and 4.406 x 10^{-5} respectively.

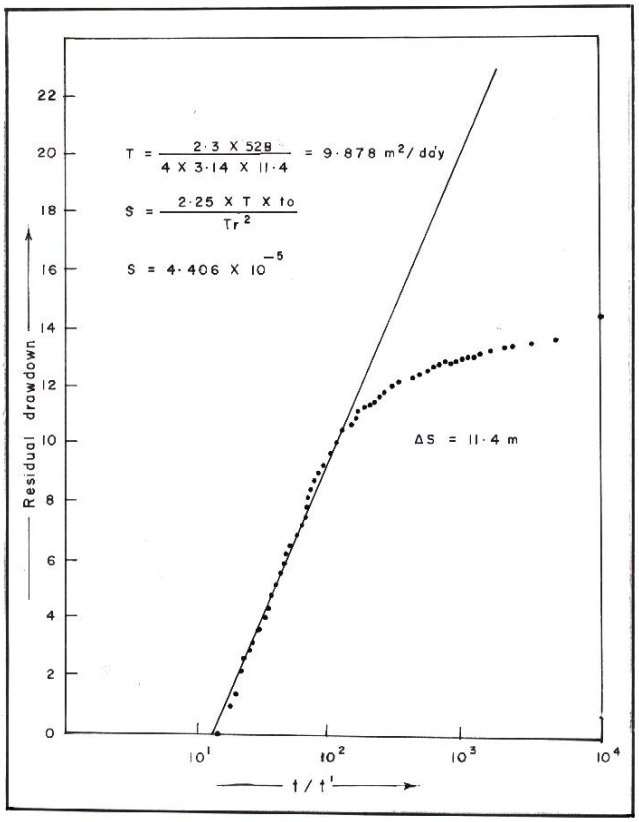

Figure 2. t/t' Vs residual drawdown plot of observation well at Meyvazhisalai village

Based on the lithological information as deciphered from the drill logs the conceptual model of the aquifer was prepared for adopting in the numerical model (Fig.3). The aquifer parameter values obtained from the analytical method were used as starting values in the numerical model for optimisation of aquifer parameter after minimising the difference between the predicted and observed drawdown of the observation wells. The USGS Modflow and Pest software were run for the purpose. During the process of optimisation several iteration runs were made so as to obtain the best fit for the observed and computed drawdowns. The Fig.4 shows the plot of measured and computer generated

plots. The optimized aquifer parameters values of transmissivity and storage coefficients derived from the numerical model are 8.2 m^2/day and 4.3 x 10^{-4} respectively.

It can be seen from the comparison of the values of aquifer parameters obtained from analytical and numerical methods that the results as obtained from the numerical approach are more dependable.

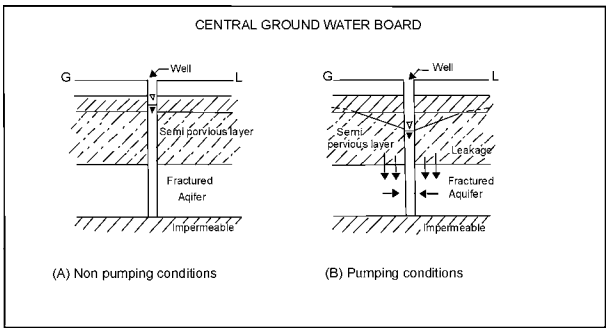

Figure 3. Conceptual model of the leaky aquifer system

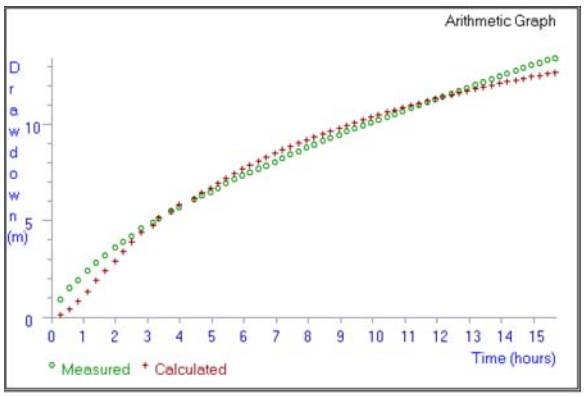

Figure 4. Plot of measured and calculated drawdowns

The effectiveness of hydraulic fracturing in hard-rock wells: case studies

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A b s t r a c t : New equipment for hydraulic fracturing of hard rock wells has been developed and tested at three locations in Norway. Furthermore, a procedure for injecting propping agent, using quartz sand, has been developed. The effect of the borehole stimulation in the three case studies is well documented by test pumping and various geophysical logging methods. A significant increase in the borehole yield can be expected as a result of hydraulic fracturing using both water-only and injection of sand. The use of sand as propping agent may be more required in fractures with high counter pressure (> 50 bars) than in fractures with lower counter pressure. The rock stress situation and the tensile strength of the bedrock have great influence on the degree of fracturing.

INTRODUCTION

Stimulation with hydraulic fracturing is a well-known technique in order to improve hard-rock borehole yields. Custom-made equipment for hydraulic fracturing in drilled boreholes, a straddle packer (pair of packers), has been developed. The straddle packer is tested to tolerate a pressure of 300 bars in the laboratory, and the working pressure should not exceed 250 bars. By using such high water pressures between the packers, the strength of the rock and the ambient rock stresses are more likely to be exceeded and a new fracture will thus be induced. Furthermore, a procedure for injecting propping agents, or grains of quartz sand, in selected borehole sections has been developed. The grains of sand are likely to act as spacing particles, and ensure an open fracture in a long-run perspective.

CASE STUDIES

Extensive tests with different kinds of hydraulic fracturing in hard rock boreholes using the straddle packer in sections of 2.5 meters have been performed at three locations, Lade, Bryn and EAB (tab.1 and fig.2). The borehole at Lade is located in the Trondheim area, while the boreholes at Bryn and EAB are located in Bærum municipality about 20 kilometers west of Oslo (fig.1).

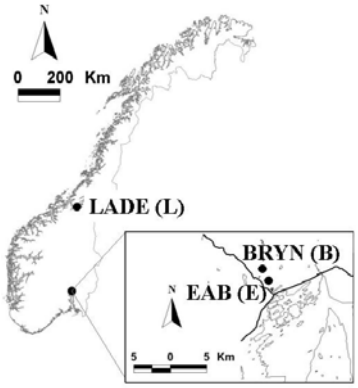

Figure 1. Geographic location and naming of the boreholes at Lade, Bryn and EAB.

Table 1. Some key information about the boreholes (bh) at Lade, Bryn and EAB

	Character of stimulation	# of bh.	Abbr.	Geol.
Lade	Hydraulic fracturing with water-only.	1	L-bh1	Green shist
Bryn	Two operations: (1) Hydraulic fracturing using water-only, and (2) hydraulic fracturing with injection of proppants.	5	B-bh1 B-bh2 B-bh3 B-bh4 B-bh5	sand-stone
EAB	One operation: (1) Hydraulic fracturing with water and injection of proppants.	3	E-bh1 E-bh2 E-bh3	Lime rich schist

The volume of sand injected into certain levels varies from 4 to 8 liters. Test pumping and geophysical logging (temperature, electrical conductivity, gamma radiation, optical televiewer and flow measurements) have been performed in order to document the effect of the different kinds of hydraulic fracturing. The borehole yield at Lade is based on short-time test pumping of the borehole, while the yields at Bryn are based on short-time sectional test pumping. Due to originally very high yields (> 7000 L/h) in the boreholes at EAB, test pumping was replaced with flow measurements performed by a continous lowering of a propeller unit in the borehole.

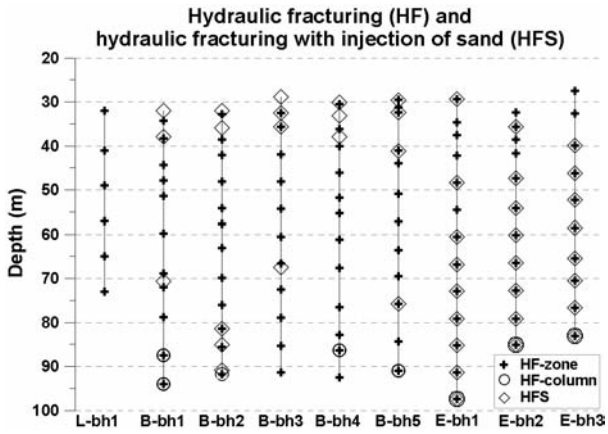

Figure 2. The character and amount of stimulation with different kinds of hydraulic fracturing in respective boreholes. "HF-zone" stands in short for hydraulic fracturing with water in sections of 2.5 meters, while "HF-column" means corresponding stimulation in columns where only the upper packer is pressurized. "HFS" means hydraulic fracturing with injection of sand, i.e. propping agents

RESULTS

Pressure-time curves from hydraulic fracturing with water-only and injection of sand are shown in fig.3 and fig.4, respectively. A distinct pressure drop in each cycle indicates the initiation or reopening of a fracture. The results from hydraulic fracturing using water-only in B-bh3, and hydraulic fracturing with injection of sand in B-bh4 are omitted due to trouble with the data logger. Manual observations of the water pressure during injection of sand in B-bh4 are given in tab.2. The stimulations always starts in the bottom of the borehole, and the first event (to the left) in the pressure-time curves, represent the lowest stimulation-level in the borehole according to the information given in fig.2. The results from the test pumping at Lade and Bryn are shown in fig.5.

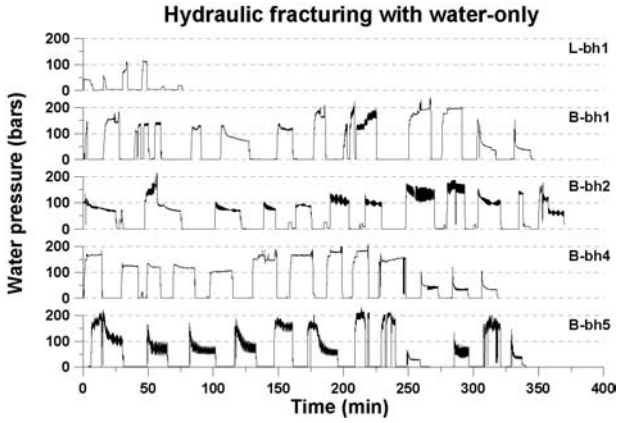

Figure 3. Pressure levels from hydraulic fracturing with water-only in the boreholes at Lade and Bryn

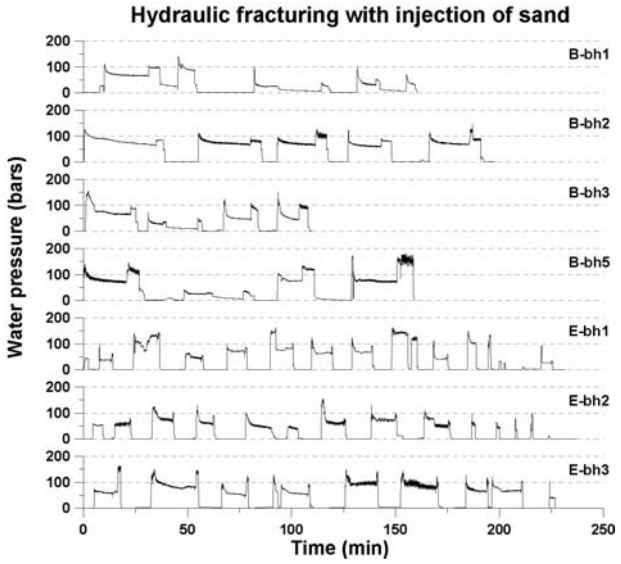

Figure 4. Pressure levels from hydraulic fracturing with injection of sand at Bryn and EAB. According to the injection of sand, a pressure rise towards the end of the stimulation cycle can be seen for most of the sections

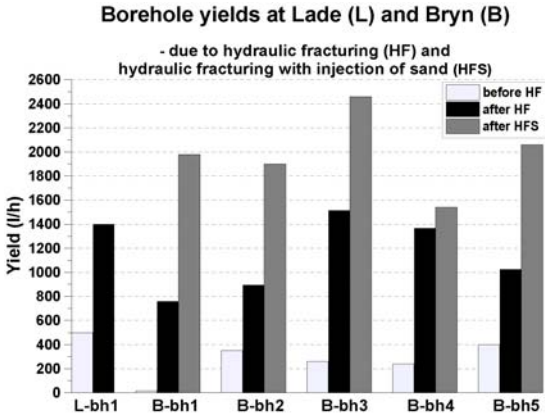

Figure 5. Results from test pumping at Lade and Bryn. Borehole yields were measured before and after hydraulic fracturing using water-only, and following hydraulic fracturing with injection of sand

Table 2. Manual observations of the water pressure during injection of sand in B-bh4

Section (m)	$P_{reopening}$ (bars)	P_{min} before inj. (bars)	P_{max} after inj. (bars)
37.9	-	35	70
33.2	-	20	65
30.1	80	30	85

DISCUSSION

Comparing the results (fig.3 and fig.4) from the different kinds of hydraulic fracturing performed at Lade, Bryn and EAB shows that the required pressure levels in order to create new fractures varies considerably. At Lade the pressure levels were too low (P_{max} ~ 120 bars) to initiate new fractures. The peak pressures present at Bryn exceed 200 bars, while the analogous pressures at EAB reaches 160 bars. At Bryn 65% (40 out of 62) of the stimulations with hydraulic fracturing were interpreted as initiation or reopening of fractures, while the number for EAB is 97% (36 out of 37). The lower degree of fracturing at Bryn is likely to be a result of high rock stresses and high tensile strength of the bedrock. Results from rock stress measurements performed in B-bh4 imply that the value of the minimum principal stress varies from 4.5-16.5 MPa, and the tensile strength of the bedrock is between 7-11 MPa (Jóhannsson 2001). Considering the bedrock at EAB, characterized as a lime rich schist, the tensile strength is assumed to be less than the values present at Bryn. The pressure-time curves from the hydraulic fracturing with injection of sand at Bryn (fig.4), even though stimulating borehole sections already fractured, show that the reopening pressure for the majority of the sections is above 100 bars. High reopening pressures imply high rock stresses.

Fig.5 demonstrates that hydraulic fracturing using water-only increases the borehole yields considerably. The same tendency is present as a result of hydraulic fracturing with injection of sand, except for B-bh4. The manually recorded water pressure data from the hydraulic fracturing with injection of sand in B-bh4, show that the minimum counter pressure before injecting the sand varies between 20-35 bars. These values are lower than most of the corresponding values registered for the other boreholes. A possible explanation of the low counter pressures registered in B-bh4 and the relatively small increase in borehole yield compared to the corresponding boreholes, could be as follows: Fractures which have a stable and low counter pressure, e.g. less than 50 bars, before the injection of sand, do have less need of sand as spacing particles compared with fractures with higher counter pressure, e.g. higher than 50 bars. A permanent increase in the borehole yield may be achieved by injecting propping agents into fractures with higher counter pressure (> 50 bars), while fractures having lower counter pressure could be considered as open and thus will remain so. The hydraulic conductivity of fractures having high counter pressures, created by hydraulic fracturing with water-only, will probably be reduced over time as the rock stresses present want to close the fracture.

CONCLUSION

The main findings in this study can be summarized as follows:

- Hydraulic fracturing with water-only results in an overall increase in the hard rock borehole yield.
- Hydraulic fracturing with injection of sand as propping agent also leads to an increased borehole yield.
- The use of sand as propping agent may be more required in fractures with high counter pressure (> 50 bars) compared with fractures with lower counter pressure.
- The rock strength and rock stresses influence the success of hydraulic fracturing with respect to the degree of reopening or opening of new fractures.

REFERENCES

Jóhannsson Æ (2001) Hydrauliske splittetester ved Bryn skole, Bærum. SINTEF Report STF22 F01126, 5 pp

ACKNOWLEDGEMENTS

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Rock massif anisotropy evaluation based on hydrodynamic testing

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A b s t r a c t : The common methods of assessment (quantification) of hydrodynamic parameters and their spatial distribution by analytical methods in anisotropic rock massif are inadequate to possibilities of numerical evaluation of special hydrodynamic tests.
We present the application of this method on two case studies:
- Performance and evaluation of hydrodynamic test in porous anisotropic aquifer to quantify hydraulic parameters in 3 D,
- Performance and evaluation of long-term group hydrodynamic test in dual porosity aquifer (porous-fracture) to assess spatial distribution of hydraulic parameters (Prostejov).
On the example of the Prostejov site the possibilities of interpretation of wider geological and hydrogeological relations of rock massif and deep geological structures by tools of numerical modelling are shown.

ROCK MASSIF ANISOTROPY EVALUATION

The submitted paper deals with applications of numerical modelling of groundwater flow with the aim to solve inverse task e.g. evaluation of hydraulic parameters in three dimensions in the complicated geological conditions.

The advantage and power of numerical modelling is in ability to describe heterogeneity and complex boundary conditions of hydrogeological structures. Utilization of wide possibilities of sophisticated software in the sphere of numerical modelling of hydrogeological processes is considerably limited by availability of input data concerning:

- Description of spatial variability of rock massif permeability (heterogenity),
- Evaluation of vertical component of hydraulic conductivity.

Heterogeneity of rock massif permeability can be studied e.g. by number of slug tests on properly distributed objects. However this is not usually the case in deep hydrogeological structures. We are going to present that numerical evaluation of long-term hydrodynamic test (one year duration) done on a group of 5 boreholes (about 200 m deep) in the complicated hydrogeological structure of Carpathian fore deep Miocene resulted in geologically reasonable idea on hydraulic conductivity distribution. The solution of problem required high conceptualisation. Complicated geological conditions are typical blar facies development of aquifer, alternation of permeable and impermeable layers, lentils and very low knowledge of tectonic structure. Miocene system of aquifers was simulated by one model layer and its calibrated transmisivity is assumed to be a rate of thickness of permeable layers. The calibration proved existence and the crucial flow-controlling role of hydrogeological structure of NW-SE direction identical with direction of geomorphologic structure of Hornomoravský úval and supposed tectonic structure direction (fig.1).

Infiltration area should be in the NNW to N, which again corresponds to geological presumptions. Mutual interferences of pumped boreholes also indicate the location of tectonic structures (non-unique explanation). After 6 months of duration of pumping tests the calibrated model was ready for predictions. The predictions were proved by continuation of pumping test and model was only slightly modified and used for optimisation of long-term exploitation of this hydrogeological structure.

The second case study being presented is aimed at numerical evaluation of special hydrodynamic tests (MODFLOW code) focused on the assessment of vertical component of hydraulic conductivity in the river valley terrace.

Three–dimensional models of groundwater flow require knowledge of vertical component of hydraulic conductivity, which cannot be evaluated by commonly used analytical methods.

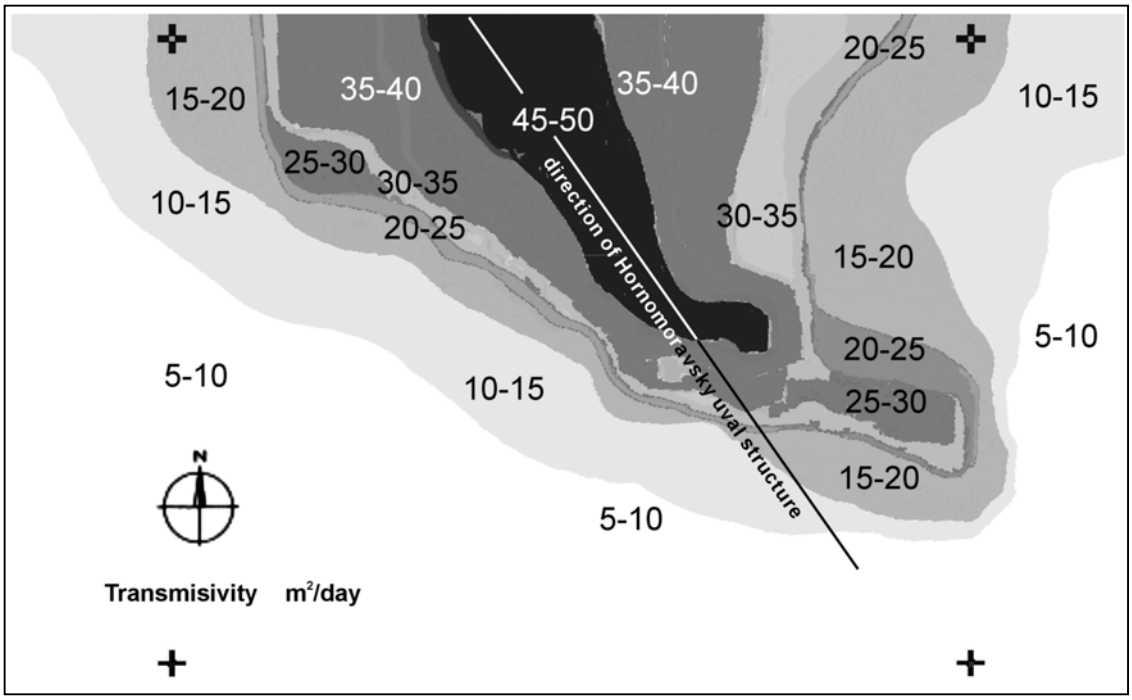

Figure 1. Calibrated transmisivity (m^2/day) after 12 months of pumping test duration

borehole		depth	construction ∅	GW level	opened layers	depth of filter	piezometer depth
pumping	EV 1	55,0	324	3,4	①	5,5-11,5	5,0-10
					②	16,5-55,0	17,0-22,0 50,0-55,0
observation	PMV 1	12,0	110	5,6	①	7,0-12,0	7,0-12,0
	PMV 2	24,0	110	3,1	①	13,5-18,0	13,5-18,0
	PMV 3	57,5	110	3,2	②	47,5-52,5	47,5-52,5

Table 1. Construction of boreholes for hydrodynamic testing

Two groups of boreholes were drilled for performance of hydrodynamic tests (1 pumping well and 3 observation wells in each group).

Construction of the first group of boreholes – see tab.1. (Rapantová *et al.* 2002)

Each of three depth horizons was pumped separately and response on all horizons opened by boreholes was observed. Further we present the results of numerical evaluation of hydrodynamic test.

Parameter	Upper horizon valley terrace	Lower horizon + subglacial channel	
		upper	lower
Hydraulic conductivity (m/s)			
horizontal K_h=	8×10^{-4}	9×10^{-4}	1×10^{-3}
vertical K_v=		3×10^{-4}	8×10^{-4}
Specific yield S_y =	0.25	---	---
Storativity S_p=	---	5×10^{-3}	5×10^{-3}

Table 2. Calibrated hydraulics characteristics

CONCLUSION

Numerical models of groundwater flow and contaminant transport become very popular especially in predictive applications. Predictions however should be done on calibrated and validated models (inverse task) realisticaly describing hydrodynamic systems with its complexity and heterogeneity..

Concerning Prostejov site (case study 1) this is the case of dual porosity environment (porous-fracture). With regard to the scale of observation we are able to define representative elementary volume (REV) with average hydraulic characteristics and use numerical models derived primarily for porous media. Similar approach proved to be suitable also for groundwater modelling in the rock massif disturbed by mine openings where system of mine workings create "pseudokarst" priority pathways (in dual porosity environment) which importance is suppressed in the regional scale of observation (Grmela *et al.* 2003).

REFERENCES

Fendeková M, Némethy P, Ženišová Z, Krčmář D, Fľaková R, (1998) The interrelationship between groundwater and streamflow - quantitative problems and anthropogenic influences, Eastern Slovakia. In Gambling with Groundwater - Physical, Chemical and Biological Aspects of Aquifer-Stream Relations, Brahana *et al.* (eds). Las Vegas: 689-695

Grmela A, Dvorský J, Rapantová N, Onderka O, Kulich V, Plášek O, Ides D (2003) Studie hydrogeologických propojení mezi ostravskou a oderskou částí zatápěné ostravské dílčí pánve. Final report HS N$^{o.}$ ZP 74/03, Ostrava 108 pp

Harbaugh,AW, McDonald MG (1996) User´s documentation for MODFLOW –96, an update to the US Geological Survey modular finite-difference groundwater flow model. Reston, Virginia: US Geological Survey, Open-File Report:96-495

Rapantová N, Grmela A, Homola V, Vojtek D (2002) Transport of pollutants in the saturated zone of Odra river valley and the upper terrace in Nova Ves groundwater withdrawal area. VŠB-HGF-IGI – Final report of project DANCEE „Complex Protection of Ostrava-Nová Ves Groundwater Source". Ostrava, 53 pp

Šilar J (1999) Zpráva o výsledku izotopového výzkumu podzemní vody ve třech vrtech v Prostějově. Závěrečná zpráva hospodářské činnosti – archív PřF UK Praha

Fractal analysis application to the temporal distribution flow drained for karstic springs in the south of Spain

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The analysis of the fractal dimension has been used as an interesting tool to characterize phenomena in Earth Sciences. The application methods to analyse the fractal dimension has been applied a few years ago to analyse and quantify the natural geometry forms and processes. Recent studies have focused on the fractal geometry techniques to study the karst phenomena and forms. In this work, we discuss the application of a simple method (scane line) to the natural flow time distribution drained by four karstic springs in the south of Spain. The Data base consists of measured daily flow (expressed in L/day) during a sequence of 15 years. The fractal dimension study has been applied to the flow time distribution from a log-log plot between the accumulated frequency of distance (difference of daily flow) and events number (number of days) (fig.1). Data of distances between flows during the time were recorded on a traverse (scan line) and the number of events were related to the difference between daily flow by a power law equation $N \propto d^{-D}$ where N is the number of days registered, *d* is the difference between daily flow and D is an exponent related to the fractal dimension of the system that was obtained applying logarithms. In the bilogarithmic plot of every temporal flow series, log- (day number)-log distance (d), the fractal dimension D(d) is the gradient of the tendency line of the distribution. The log-log plot shows that the temporal sequence of flow by every spring presents several tendency lines with different gradients as the series supports multifractal spectra (fig.1). However, the comparison between the principal tendency lines of every spring also shows differences between them that can be related with the anisotropy degree of the carbonate mountains. The D(d) obtained is different in every spring suggesting that this type of analysis could be a simple tool that can show the karstification degree of an aquifer.

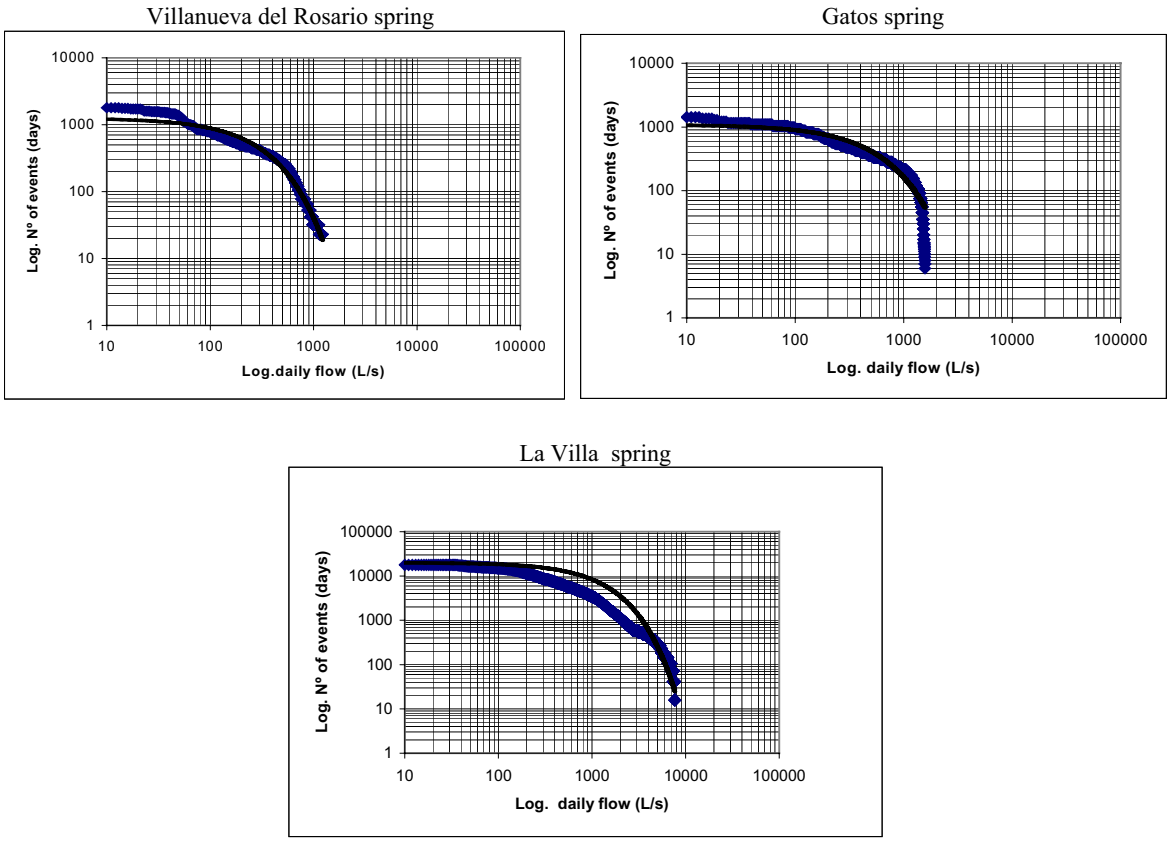

Figure 1. Distance variaton between flow days in Villa-Nueva del Rosario, Gatos and La Villa springs

Interconnected flow measurement between boreholes using a borehole flowmeter

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A b s t r a c t : Pumping tests were carried out in a group of nine boreholes in granitic rock. A sensitive flowmeter called Posiva difference flow meter was used to measure the flow response. "Background" flow rates were first measured in all boreholes without pumping. One borehole was pumped at a time and flow responses were measured in all boreholes, including the pumped borehole. The boreholes were open during all the tests and flowrates were measured at two meters intervals. For interpreting the results, a simple electrical equivalence was applied. An interesting interpreted parameter is interconnected flow, a portion of measured flow that is caused by pumping from a near borehole. It can be expressed as percent of pumping rate. Clear interconnected flow responses were detected. They were strongly concentrated in few fractures. Assessment of all the pumping responses in a three-dimensional fracture network is only possible with numerical modelling. In such modelling the open boreholes can also be taken into account as essential hydrogeologic features.

MEASUREMENTS

The distance between the boreholes varies from 10 m to 100 m. All the measurements were carried out in open boreholes, i.e. no packers were used. For interpretation, each borehole was first tested as normal single hole test, flow rates and drawdown were first measured both without pumping and with pumping the borehole under test. The boreholes were measured with 2 m sections, depth intervals where flow rates were measured. Flow into or out from the borehole was monitored in these sections in such a way that all intervals in the boreholes were covered. The same depth intervals were used both in the single hole tests and in the interference tests.

During the interference tests, each pumping borehole — KR14, and KR15A to KR18A — was pumped at a time and head response (change in drawdown) and flow responses (flow rates in the test sections) were measured in the other boreholes, including shallow boreholes KR15B to KR18B (Fig.1).

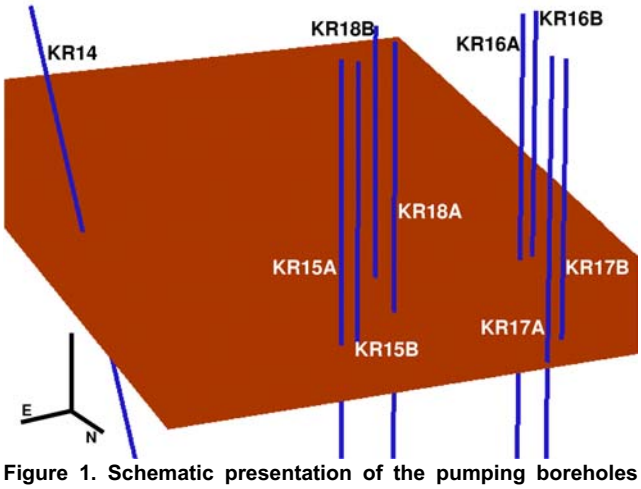

Figure 1. Schematic presentation of the pumping boreholes (KR14, and KR15A to KR18A) and shallow boreholes (KR15B to KR18B) in which the pumping responses were also measured. In the figure, the boreholes are intersected by a hypothetical fracture

INTERPRETATION

A simple equivalent electrical circuit was used for the interpretation of the results, see Fig.2. Equivalent circuit can be created for various structures as bands or plates. Hydraulic conductivity with geometrical parameters can be converted to conductance, inverse of resistance. The boreholes are electrical short cuts in the model as they are hydraulic short cut in the bedrock. Flow converts to electric current and head converts to voltage.

The measured parameters are head in boreholes A and B and the flow rates in borehole B measured in two-meter sections. Three tests are applied to each pair of boreholes: neither borehole is pumped, borehole B is pumped and borehole A is pumped. This leads to nine equations with nine unknowns. The unknowns to be solved are conductance G1 and conductance G2, distant potential Uo and flow rates in the mentioned three tests Ia and Iu., see Fig.2. The interconnected flow can be defined as a difference of flow Iaa when A is pumped and Iao when no borehole is pumped. It can be expressed as percent of the pumping rate from borehole A.

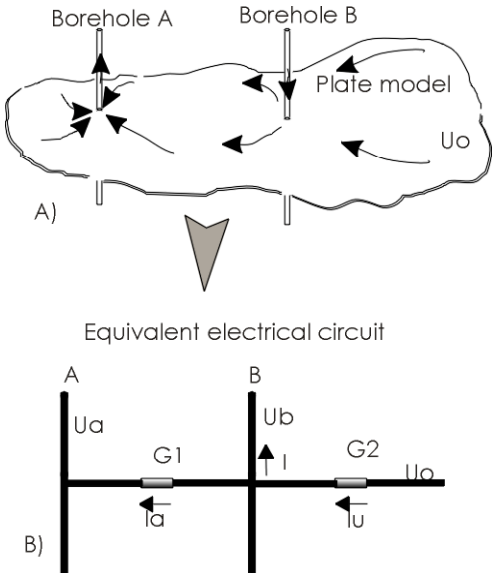

Figure 2. Equivalent electrical circuit for rock formation

RESULTS

Both head and flow responses were clear in all boreholes. An example of results is presented in Fig.3. Both boreholes KR16 and KR18 were pumped in turn. The red bar shows the calculated interconnected flow in percent of the corresponding pumping rate from the other borehole. In both cases the highest response is much larger than the other ones (note the logarithmic scale). High response (almost 20 % in both cases) cannot be explained by a homogenous two-dimensional model.

Typical features in all measured boreholes were:

-Flows were concentrated in the upper part of the bedrock

-Flows were concentrated in few zones

-The highest flow responses were higher than can be explained by a homogenous two-dimensional model.

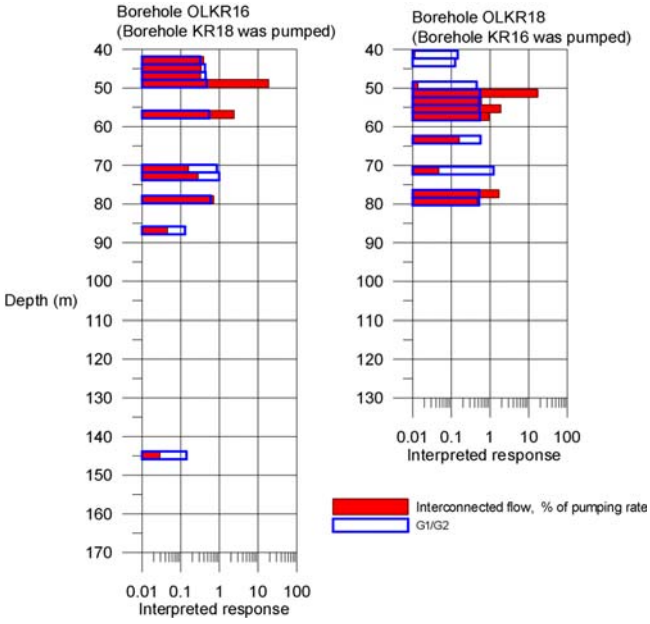

Figure 3. Example of responses between two boreholes

The other drawn parameter is the ratio of conductances between the borehole and outside the measured borehole, the blue bar in Fig.2. It has less correlation to hydraulic conductivity than the calculated interconnected flow. If it is larger than one, the continuation of the zone is poor behind the measured borehole. If it is near 0.1, the zone has higher hydraulic conductivity behind the measured borehole than between the boreholes.

Modelling of the pumping responses in a "full" three-dimensional space is only possible with numerical means. In these computations the open boreholes can also be taken into account as essential hydrogeologic features.

CONCLUSIONS

Advantages of the method are:

- It is relatively fast because there is no need to wait pressure stabilization in a new position of flow measurement (open boreholes).
- It can detect and quantify the main connections between the boreholes.

Disadvantages are:

- It does not proof which zone belongs to which one in different boreholes
- For the present it is difficult to explain the high flow and head response. In order to explain them, one has to apply numerical means to model the pumping responses in a three-dimensional fracture network.

REFERENCES

Rouhiainen P (2001) Posiva groundwater flow measuring techniques. Proceedings of the XXXI International Association of Hydrogeologists Congress Munich/Germany/10-14 September 2001. New Approaches Characterizing Groundwater Flow Volume 2, ISBN 90 2651 850 1

Ludvigson J-E, Hansson K, Rouhiainen P (2002) Methodology study of Posiva difference flow meter in borehole KLX02 at Laxemar. SKB Rapport R-01-52

GIS-based vulnerability maps of groundwater to acid deposition: application to the Grío river basin (Zaragoza, Spain)

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Abstract: A method for constructing groundwater vulnerability maps based on Geographical Information Systems (GIS) has been developed as a tool for groundwater resources protection. Maps were elaborated using four auxiliary layers, each one reflecting a particular parameter that governs acidification. Factors determining vulnerability are: elevation above mean sea level, morphology of the terrain, areal extent and type of vegetation cover, and geology. The method has been applied to the Grío river basin. The vulnerability map thereby obtained has been contrasted with chemical data from springs and streams of the study area.

INTRODUCTION

Groundwater acidification is a great environmental problem in countries of Nordic and Central Europe. This phenomenon affects as much to the flora as to the fauna, not only by the descent of the pH, but also by the increment of contents in toxic metals (aluminium and cadmium) and by the loss of nutrients in the soil. Groundwater acidification also causes serious damages to the forests and crops. It has been demonstrated that certain agricultural practices, such as the excessive use of fertilisers, diminish the neutralisation capacity of the ground, therefore increasing the effects of acidification (Thunberg and Hanneberg 1987).

Physical-chemical analysis of rainfall water have been carried out worldwide for the study of this phenomenon. Nowadays there are two main control nets: the European net **EMEP** (Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe) and the North American **NADP** (National Atmospheric Deposition Program). However, acidification of groundwater does not only depend on the characteristics of the rainwater, but also on the capacity of the lands to neutralise them. Neutralisation is near to total in karstic regions. On the contrary, neutralisation capacity of granitic lands is very poor, being especially vulnerable to groundwater acidification.

In the case of the Iberian Mountains, at the moment it does not seem to exist serious issues of acidification neither in surface flows nor in groundwater, except in some areas next to thermal power plants. Actually, pH values in rainwater are higher than 6 and, in some cases, between 7 and 8. The dry deposition is very important in the whole area. Generally, it shows a neutralisation and alkalisation effect due to the presence of calcite powder (Mediterranean water) and it only produces acidification in areas located next to thermal power plants, as it happens in the study area (thermal power plant of Andorra, located about 100 km away).

Under this situation of localised problems, maps of vulnerability to acidification are especially appropriate because they permit to locate potentially problematic areas. This type of maps are frequently accomplished in countries where the acid rain is an important environmental problem. It is the case, for example, of the Czech Republic (Hrkal 2001).

APPLICATION TO THE GRÍO RIVER BASIN

The study area (Fig.1) is located in the northeastern sector of the Iberian Peninsula, within the Iberian Mountains, next to its boundary with the Tertiary Ebro basin. The area embraces the headwaters of the Grío river basin, a tributary to the Jalón river by its right margin. The Grío river drains the ranges of Vicort and Algairén which are build up mainly by Palaeozoic quartzite and shale.

The software ARCVIEW has been used for the elaboration of vulnerability maps to acidification, as a Geographical Information System. The methodology is based on the study for the separation of different vulnerability factors to acidification (Hrkal, 2001).

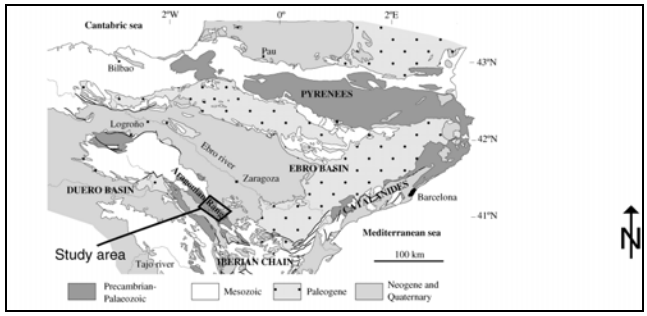

Figure 1. Location of the study area

Low pH values in groundwater are related to contributions of acids, both dissolved in the rainwater (humid deposition) and present in the powder carried by the wind (dry deposition), and also to the capacity of the ground to neutralise this acidity. The main factors that control these parameters are: altitude, orientation of the hillsides, extension and type of vegetation cover, and geology.

Vulnerability factors associated to the altitude

In general, groundwater vulnerability to acidification increases with the altitude. Usually, the higher altitude, the more abundant rainfalls. Thus humid deposition is bigger and the capacity of the ground to neutralise acidity is lower. Springs in high areas are related to local groundwater flows with low residence times and, therefore, they are very influenced by the characteristics of the rainfall water. The study area has been divided into three areas whose boundaries are the contour of 800 m, where the range begins, and the contour of 1,100 m, where the climatic change is significant (bigger rainfall and smaller evapotranspiration).

Vulnerability factors associated to the hillsides orientation

As a result of the predominant wind direction and the relief analysis, it is observed that hillsides facing the dominant wind have a higher vulnerability to the dry deposition. Wind blows from variable directions in this area of abrupt topography, but wind from WNW is predominant, receiving the name "cierzo" (Faci and Bercero 1991).

Vulnerability factors associated to the vegetation cover

Groundwater acidification also depends on the extension and type of vegetation cover. Areas without vegetation cover or prairies do not catch the dry atmospheric deposition, since most of this is taken again by the wind. On the contrary, mature forests have a great surface which catch the powder that is dragged by rainwater toward the soil, acidifying the groundwater.

Vulnerability factors associated to the geology

There are mainly two geologic factors that control aquifer vulnerability to acidification: lithology (giving the possibility to occur neutralisation reactions between acid water and rock) and permeability of the materials (residence time of the water within the rocks).

RESULTS

The sum of vulnerability degrees for each of the considered factors allows to outline the spatial distribution of five numeric, vulnerability levels of groundwater to acidification in the area (Fig.2).

The five vulnerability levels established are:

- ***Very high (risk degree over 7.8) and high (between 6.6 and 7.7) vulnerability.*** Generally they correspond to the highest areas in the ranges, located on quartzitic rocks and covered by conifer forests, with the maximum rainfalls for the study area. In the Vicort range, slightly acid pH values have been measured (up to 6.6, and concentrations of HCO_3^- lower than 80 mg/L, indicative of a light groundwater acidification.

- ***Medium vulnerability (between 5.6 and 6.5).*** This characterises transitional areas with regard to the probability that groundwater acidification is taking place.

- ***Low (between 3.8 and 5.5) and very low (below 3.8) vulnerability.*** They correspond to areas out of risk of acidification. They are low altitude, flat areas with scarce rainfalls and without arboreal cover.

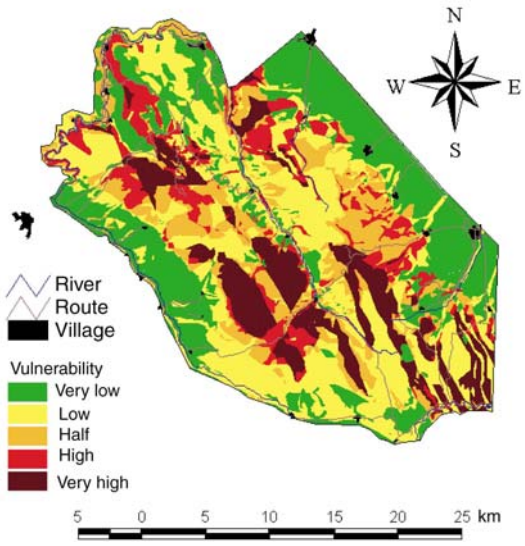

Figure 2. Vulnerability map of groundwater to acid deposition

CONCLUSIONS

Unlike to Central and Northern Europe, where acidification is a serious environmental problem, this is not a prominent issue in our study area, located in the Iberian Mountains under Mediterranean influence. The nature of the Mediterranean rains and the importance of the dry deposition, frequently of calcareous powder, lead to rainwater pH values above 6, even between 7 and 8. Local acidification problems affecting soils and vegetation arise only in areas next to thermal power plants, as that of Andorra (Teruel), due to gases and mainly to S particles. In these circumstances, the accomplishment of maps of vulnerability to acidification is especially useful since they summarise the areas where such problems can take place. Summarising for the Vicort range, the most vulnerable places correspond to the quartzitic rocks, topographically located in the higher areas, with arboreal vegetation cover, especially of conifers. Recovery of the autochthonous vegetation (*Quercus*) can be an appropriate measure for improving and preserving the environmental conditions of the area.

Acknowledgements

This work has been carried out in the framework of the Project LOWRGREP (*Landscape-use Optimization With Regards of the Groundwater Resources Protection in the mountain Hardrocks areas*) financed by European funds.

REFERENCES

Faci J, Bercero A (1991), Efecto del viento en las pérdidas por evaporación y arrastre en el riego por aspersión. Investigación Agraria 6(2):171-182

Hrkal H (2001) Vulnerability of groundwater to acid deposition, Jizerske Mountains, northern Czech Republic: Map construction and reliability of a GIS-based vulnerability. Hydrogeology Journal 9(4):348-357

Thunberg B, Y Hanneberg P (1987) Acidification and air pollution. Pb. Swedish Environmental Protection Agency. 93 pp Solana

Geophysical methods for groundwater exploration in Ocotal, northern Nicaragua

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A b s t r a c t : In the northern part of Nicaragua water supply has become an increasing problem as groundwater resources are scarce and surface water is being affected by human activities. The natural disaster in 1998 caused by hurricane Mitch gave an alert on water resources management as many sources became contaminated during floods. The need to explore groundwater sources in the surroundings of Ocotal, northern Nicaragua is increasing. This geophysical survey including twenty-four Vertical Electrical Soundings (VES) and three Continuous Vertical Electrical Soundings (CVES) was carried out combined with a geological reconnaissance to identify the aquifer formations in the area. Two regions with favourable signatures for groundwater occurrence located in the north and east part of the area were identified.

INTRODUCTION

In the northern part of Nicaragua, water supply becomes an increasing problem as water resources are getting scarce and affected by human activities. The natural disaster caused by hurricane Mitch in 1998 gave an alert on the need to develop water resources management as many sources got contaminated with sewage during floods. This investigation was carried out within the framework of an assistance programme funded by the European Union, with the aim of finding new groundwater sources.

The city of Ocotal is located 226 km north from the capital Managua. The area is drained by the uppermost part of the Coco river basin, one of the biggest in Central America, and 87% of the total population (32000 inhabitants) of the city is supplied with water from a surface source (PIEO 2003). The investigated area is 17 km^2 of a rather flat valley (fig.1).

The geology of the area is characterised by the presence of a silica and feldspars rich Quaternary alluvial which is overlaying well fractured and folded schist rocks formed during Palaeozoic (Dengo 1973). Limestone is found northwest of the area (Del Giudice 1960) and several fractures systems cross the area in northeast direction

METHODS

Geological reconnaissance preceded by aerial photo interpretation was done in the area with the aim to understand the main stratigraphic and tectonic features. Special attention was given to geological and structural characteristics that might be related to groundwater presence. Observations in dug and drilled wells were made to measure water levels and document the stratigraphy.

The Vertical Electrical Soundings (VES) were well distributed to cover most of the area and be able to characterise the response at different locations. For the soundings a total of twenty-four VES were carried out by using a Terrameter ABEM SAS4000 with the maximum AB spread of 600 m.

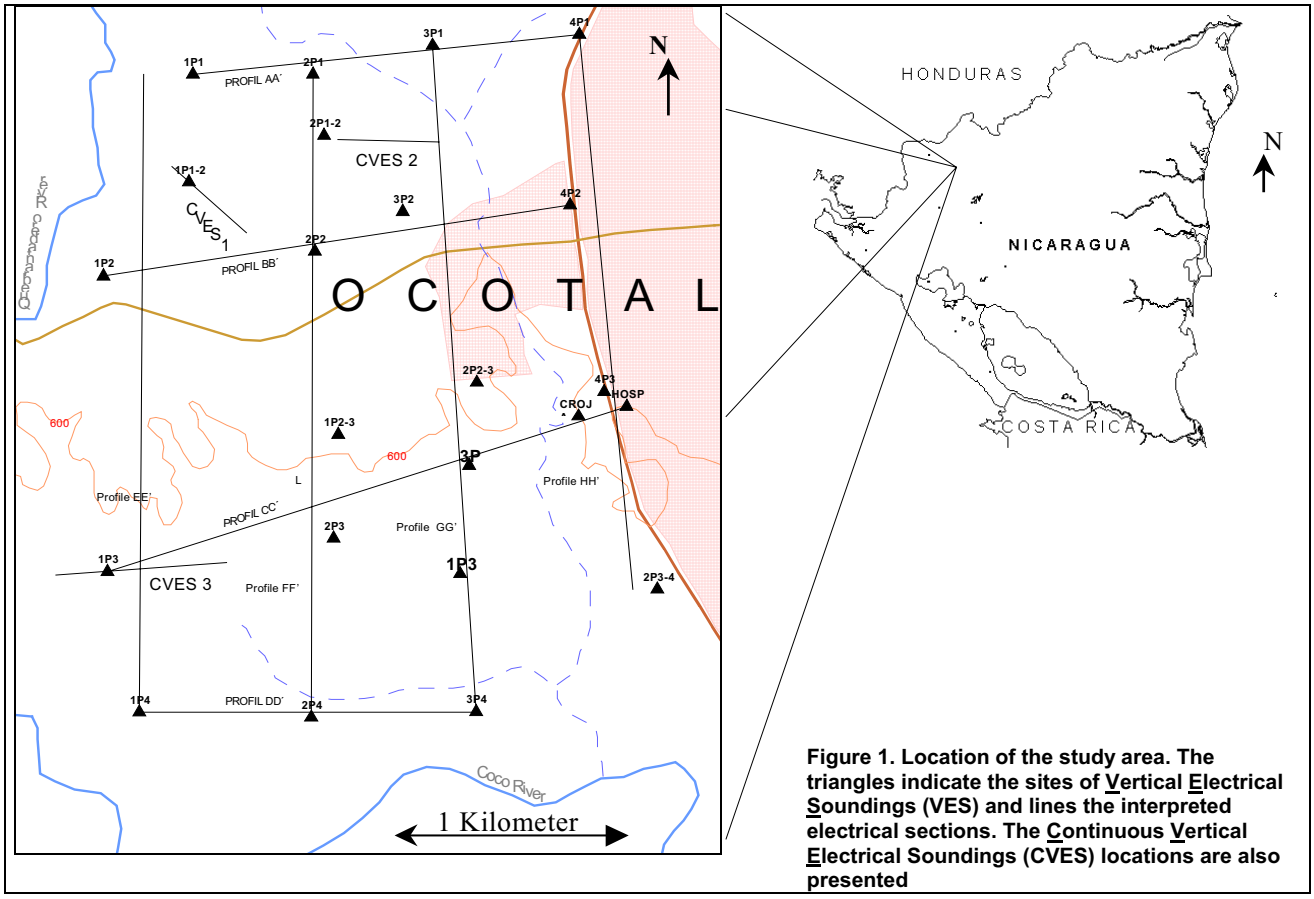

Figure 1. Location of the study area. The triangles indicate the sites of Vertical Electrical Soundings (VES) and lines the interpreted electrical sections. The Continuous Vertical Electrical Soundings (CVES) locations are also presented

In situ measurements of the resistivity response from different materials present in the area were also made, -using a miniature Wenner array (a=0.1m)-, in order to support the resistivity survey results interpretation.

RESULTS

The only two springs found in the area are aligned with a main local fault. This fracture can be observed at 500 m on the resistivity inversion of CVES3 (fig.2).

With the results of the vertical soundings, eight electrical sections were developed. From these electrical sections it was possible to identify four layers; Layer A with resistivity values <20 ohm-m, Layer B with values from 20 Ohm-m to 75 Ohm-m, Layer C with values from 75 Ohm-m to 150 Ohm-m and Layer D with resistivity values >150 Ohm-m (fig.2).

The lower resistivity values (Layer A) are here interpreted as black clay and schist. This fractured metamorphic unit is often overlaid by rather resistive coarse sand with interlaced brownish lime (Layer B). The latter has better conditions to form an aquifer. The uppermost thick alluvial gives the higher resistivity responses of Layers C and D.

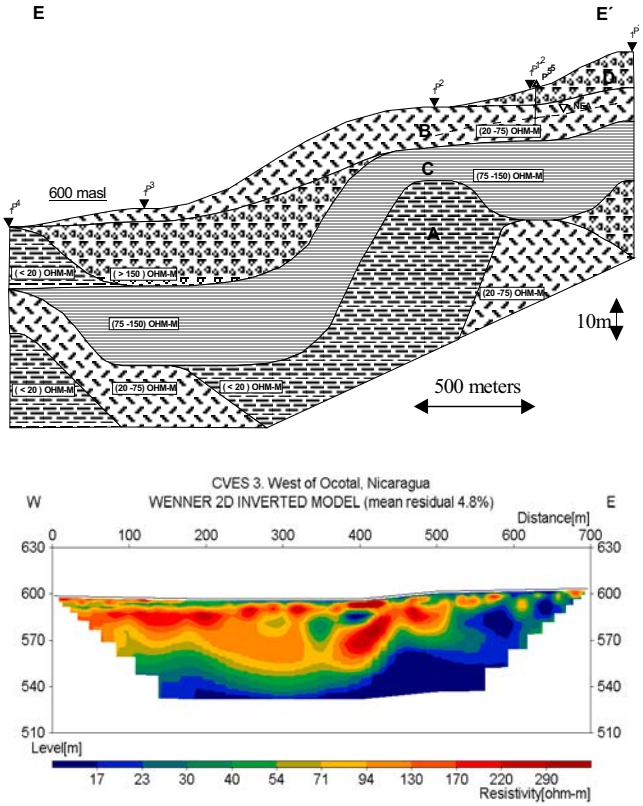

Figure 2. Example of results. Above, electrical section EE' from south to north. Below, inversion result of one Continuous Vertical Electrical Sounding (CVES3)

The inversion results of the CVES indicate resistivity values that match well with the results from the vertical soundings. Based on observations of water levels in wells and the geology background, the areas with resistivity values from 17 Ohm-m to 54 Ohm-m are propitious to groundwater occurrence (see fig.2).

CONCLUSIONS

In the study area the aquifer is characterised by resistivity values ranging from 20 Ohm-m to 75 Ohm-m. The aquifer thickness is around 30 m and the mean depth to groundwater is 10 m. According to the geoelectrical results there are two areas with more favourable conditions for groundwater occurrence, one in the northern part of the area, and another in the eastern part. Groundwater stored in the aquifer might be discharged through fractures and faults, decreasing the available groundwater volume.

ACKNOWLEDGEMENTS

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The authors would like to thank the Centro de Investigaciones Geocientíficas (CIGEO/UNAN) and the Swedish International Development Authority (Sida/SAREC) for their support to geoscientific research in Nicaragua.

REFERENCES

Dahlin T (1996) 2D resistivity surveying for environmental and engineering applications. First Break 14(7):275-283

Del Giudice D (1960) Apuntes sobre la geología de Nueva Segovia [Notes on the geology of Nueva Segovia]. Boletín del Servicio Geológico Nacional de Nicaragua 4(1):17-37

Dengo G (1973) Estructura geológica, neotectónica y morfología de América Central [Geological structure, neotectonics and morphology of Central America]. México, Centro Regional de Ayuda Técnica, 52 pp

Loke MH (1999) Rapid 2D resistivity and IP inversion using the least–squares method. Geoelectrical Imaging 2D and 3D, Software manual, 81pp

PIEO (2003) Censo de Pozos y Ojos de Agua en el Valle de Ocotal [Inventory of wells and springs in the Ocotal valley]. Proyecto Integrado Estelí- Ocotal. Internal Report R1/AP/Ocotal/CM

Interpretation and analysis of aquifer tests in fractured - karstified carbonate limestone

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A b s t r a c t : This paper presents a method to interpret drawdown and residual drawdown data of pumping tests in fractured (karstified) limestone on the basis of the double-porosity concept. With Kazemi's *et al. (*1969) straight line method, the aquifer characteristics of transmissivity and storativity of both pumping and recovery stage are mathematically formulated without any correction or additional assumption. An actual case is shown to illustrate the proposed method. The methodology presented in this paper can be extended to various situations where the concept of double porosity is applicable.

The method we present here is based on the double-porosity theory, which conceptualizes the fractured rocks as a composition of two media: the fractures of high permeability and low storage capacity, and the matrix blocks of low permeability and high storage capacity. Pumping tests in the fractured rocks often exhibit drawdown curve of three distinct phases, that is:
(1) Early pumping time, when most of the groundwater flows from storage in the fractures, and the drawdown is described in 2D 'depth averaged ' conditions by the Theis's equation (Theis 1935)

$$s_1 = \frac{Q}{4\pi T} W\left(\frac{S_f r^2}{4Tt}\right) \qquad (1)$$

where s is the drawdown observed at a distance r, Q is the pumping rate, $W()$ is the Theis well function, S_f is the storage coefficient or storativity mostly of the fracture network, T is the aquifer transmissivity.
(2) Medium pumping time, a transition period during which a relative stabilization of the drawdown is observed due to the increasing drainage of the groundwater coming from the porosity of the matrix blocks. In a drawdown versus log time diagram, this phase is characterized by an inflection point and sometimes a nearly constant drawdown for certain time interval.
(3) Late pumping time, when it can be considered that the pumped water comes from storage in both the fractures and the matrix blocks

$$s_3 = \frac{Q}{4\pi T} W\left(\frac{\left(S_f + S_m\right) r^2}{4Tt}\right) \qquad (2)$$

where S_m is the storativity of the matrix blocks. Given small values of r^2/t, Eq. (1) and (2) can be replaced by the Cooper-Jacob approximation (Cooper *et al.* 1946) as

$$s_1 \approx \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{S_f r^2}\right)$$

and

$$s_3 \approx \frac{2.3Q}{4\pi T} \log\left(\frac{2.25Tt}{\left(S_f + S_m\right) r^2}\right) \qquad (3)$$

which can be used to compute T, S_f and S_m with the standard procedure outlined for the Kazemi *et al.'s* straight-line method (Kazemi *et al.* 1969; Kruseman and de Ridder 1994).

As the pumping stops, the recovery starts. Given the pumping test has progressed sufficiently far in the 3rd phase the recovery will also exhibit three distinct phases. In the first phase, the fractures are quickly recovering and the drawdown can be calculated on the basis of superposition principle as follows

$$s_1' = \frac{Q}{4\pi T} W\left(\frac{\left(S_f + S_m\right) r^2}{4Tt}\right) - \frac{Q}{4\pi T'} W\left(\frac{S_f' r^2}{4T't'}\right) \qquad (4)$$

where the superscript ' corresponds to the characteristics of recovery stage and t' is elapsed time since the pumping ceases.
The second phase is again a transition period when also gradually the pore matrix is recovering. In the 3rd phase both the fracture network and the matrix blocks are recovering, which can be calculated by

$$s_3' = \frac{Q}{4\pi T} W\left(\frac{\left(S_f + S_m\right) r^2}{4Tt}\right) - \frac{Q}{4\pi T'} W\left(\frac{\left(S_f' + S_m'\right) r^2}{4T't'}\right) \qquad (5)$$

The Cooper-Jacob approximation for Eq. (4) and (5) when $T \approx T'$ is expressed as follow:

$$s_1' \approx \frac{2.3Q}{4\pi T} \log\frac{S_f' t}{\left(S_f + S_m\right) t'}$$

and

$$s_3' \approx \frac{2.3Q}{4\pi T} \log\frac{\left(S_f' + S_m'\right) t}{\left(S_f + S_m\right) t'} \qquad (6)$$

For hard rock, the pumping does not create a mechanical consolidation of the aquifer, but it can modifies slightly its compressibility during loading (pumping) and unloading (recovery), which results in $S_f \neq S_f'$ (and $S_m \neq S_m'$). More important, the obtained transmissivity values in pumping and recovery conditions can be quite different due to a number of factors. For instance, if the borehole was not entirely cleaned before the pumping test is carried out, the pumping has possibly removed most of the muddy materials present in the fractures facilitating the groundwater flow towards the well in the further recovery stage (i.e., T increases). When $T \neq T'$, an estimation of T', S_f' and S_m' is still possible using the Cooper-Jacob approximation for Eq. (4) and (5) as follow

$$s_3^* - s_1' \approx \frac{2.3Q}{4\pi T'} log\frac{2.25T't'}{S_f' r^2}$$

and

$$s_3^* - s_3' \approx \frac{2.3Q}{4\pi T'} log\frac{2.25T't'}{\left(S_f' + S_m'\right) r^2} \qquad (7)$$

where * corresponds to the pumping drawdown extended with Eq. (3) for $t > t_p$ where t_p is the time since the pumping was

stopped (Fig.1). It is worth noting that the extrapolated values of the pumping drawdown depend on the quality of the value of T obtained with Eq. (3). Consequently, any inaccuracy or error in the drawdown is carried over into the estimation of the characteristics of the recovery stage.

An example of the proposed method is presented here with an application of a pumping test that is carried out in fractured and karstified carbonate rocks in the Northwest of Vietnam. The drawdown data are measured in the pumped well. Therefore, the storativity (in both pumping and recovery stages) cannot be accurately evaluated. The pumping stopped at t_p = 1320 min. The drawdown record starts at time t = 15 min, therefore, evaluation of the 1st phase of pumping stage was unfortunately not possible. The transmissivity, T, estimated during the pumping stage is evaluated to 10.5 m^2/d. The straight line of the 3rd phase is extended which enables to compute quantity $s - s'$ for recovery duration. Finally, the transmissivity, T', evaluated during the recovery stage is 25.8 m^2/d.

In conclusion, the proposed interpretation methods of pumping and recovery drawdown allow, when used jointly, to estimate explicitly the transmissivity and storativity for both pumping stage and recovery stage. In the application of the methods, attention must be paid to the extension of the pumping drawdown for the interval after the pumping stops.

REFERENCES

Cooper HH, Jacob CE (1946) A generalized graphical method for evaluating formation constants and summarizing well field history. Am Geophys. Union Trans 27:526-534

Kazemi H, Seth MS, Thomas GW (1969) The interpretation of interference tests in naturally fractured reservoirs with uniform fracture distribution. Soc of Petrol Engrs J, pp 463-472

Kruseman GP, de Ridder NA (1994) Analysis and Evaluation of Pumping Test Data, Second Edition. ILRI publication 47, 377 pp

Theis CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. Trans. Amer. Geophys. Union 16:519-524

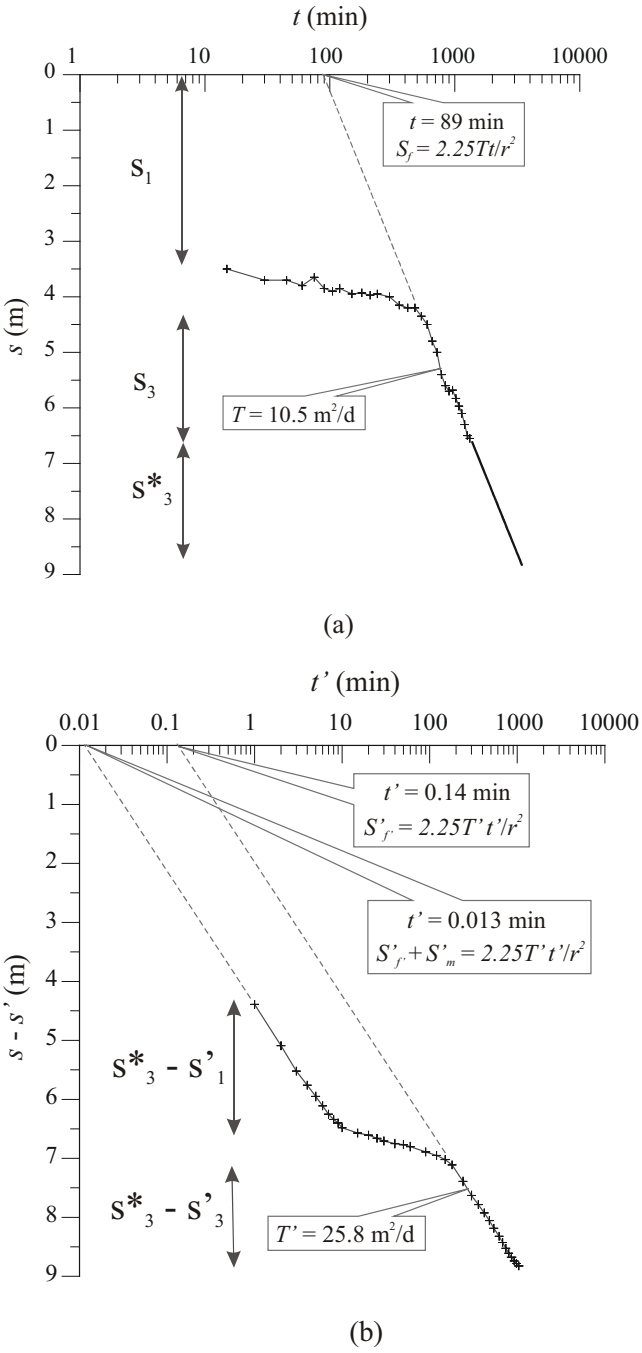

Figure 1. Semi-log plot of (a) pumping drawdown vs. pumping time and (b) s - s' vs. recovery time

A tracer investigation into the importance of diffusive exchange in the unsaturated zone of the British Chalk

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A b s t r a c t : This paper describes a comparative tracer study on the Middle Chalk in Cambridgeshire, East-England, to investigate fracture flow and diffusive exchange between fractures and matrix in the unsaturated zone. The experiment, on a lysimeter under natural rainfall conditions, uses deuterium and bromide as tracers. After one winter recharge season, none of the tracer has appeared in the lysimeter drainage, indicating that bypass flow within the fracture space has not led to tracer transport to 5m. Vertical core profiles showed that the bulk of the tracer has migrated very little, but that there is some evidence of fracture flow with secondary peaks down to 1.5m depth. The experiments highlight the high attenuation capacity of the soil cover and the chalk unsaturated zone, but demonstrate that even for moderate rainfall conditions some bypass flow is possible.

INTRODUCTION

The water quality in European aquifers is at risk from anthropogenic contaminants, both from diffuse and point sources. An economically and ecologically important aquifer in England and in other countries of North-West Europe is the Chalk, and its vulnerability to pollution is a source of ongoing concern.

The Chalk is a fractured rock with a fine-grained porous matrix, where the fractures greatly enhance the permeability, and the matrix provides most of the porosity and storage capacity. Migration of water and solutes through the unsaturated zone is not fully understood, as the flow process may be the result of a complex interaction between both domains. In general, it is assumed that a substantial part of the flow goes through the matrix pores as piston displacement, and fracture flow is only generated during periods of high recharge rates. Hence the unsaturated chalk is a double-permeability medium, albeit with widely contrasting velocities: for bypass flow through fractures, transport velocities of more than 1 metre a day can be reached, while for piston flow displacement through the matrix a transport velocity of not more than 1 metre a year is common.

For solute transport, diffusion can occur between the mobile fracture-water and the nearly static matrix-water, and the extent of this diffusive exchange largely determines the velocity of solute transport to the groundwater table. In this respect two extreme situations can be visualized. In the first one, fracture flow allows complete diffusive equilibrium with the surrounding matrix (fig.1a). At any point along the fracture the solute concentrations of the fracture and its surrounding matrix will be equal (this situation was called the "chromatographic approximation" by Barker and Foster (1981)). The opposite situation arises when no diffusion exchange is occurring at all (fig.1b). In this case the solutes effectively by-pass the matrix and can travel quickly towards the water table without any considerable attenuation. Yet, the actual field situation for any given site is likely to vary considerably between these two extremes (fig.1c). In this case some solute bypasses the matrix, but the solute load of the fracture water is gradually attenuated along its transport through the fracture because of progressive loss of solute into the matrix. Recently, the whole concept of continuous fracture flow has been questioned by Price *et al.* (2000). They argued that fracture flow could be generated at any point in the unsaturated zone, as long as the matric potential rises to a level that is high enough to cause a meniscus to bridge a fracture in its narrow paths (fig.1d). In this case the fracture flow is derived from the matrix, and might eventually return to the matrix where the matric potential drops again. This implies that on top of diffusive exchange between fractures and matrix, advective exchange is possible as well.

Thus there is a lot of uncertainty about the conditions that trigger bypass flow and about the extent of diffusive interchange between fractures and matrix. Field experiments on unsaturated chalk are limited, and tracer tests done so far were mainly run under artificially high infiltration rates. This paper presents a tracer test run on an undisturbed field lysimeter under natural rainfall conditions.

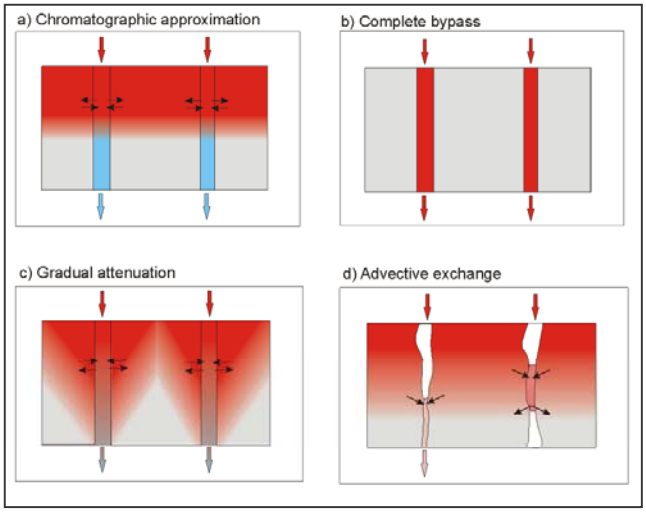

Figure 1. Scenarios of solute exchange in unsaturated chalk

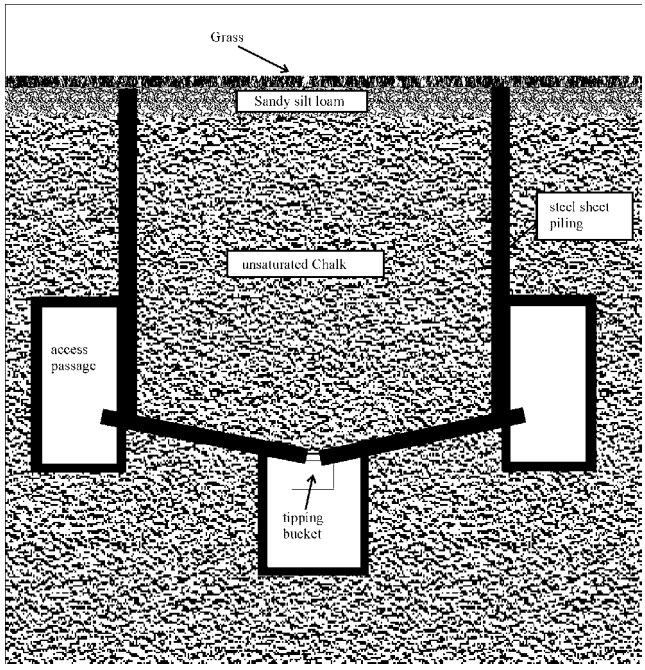

Figure 2. Cross-section of Fleam Dyke lysimeter

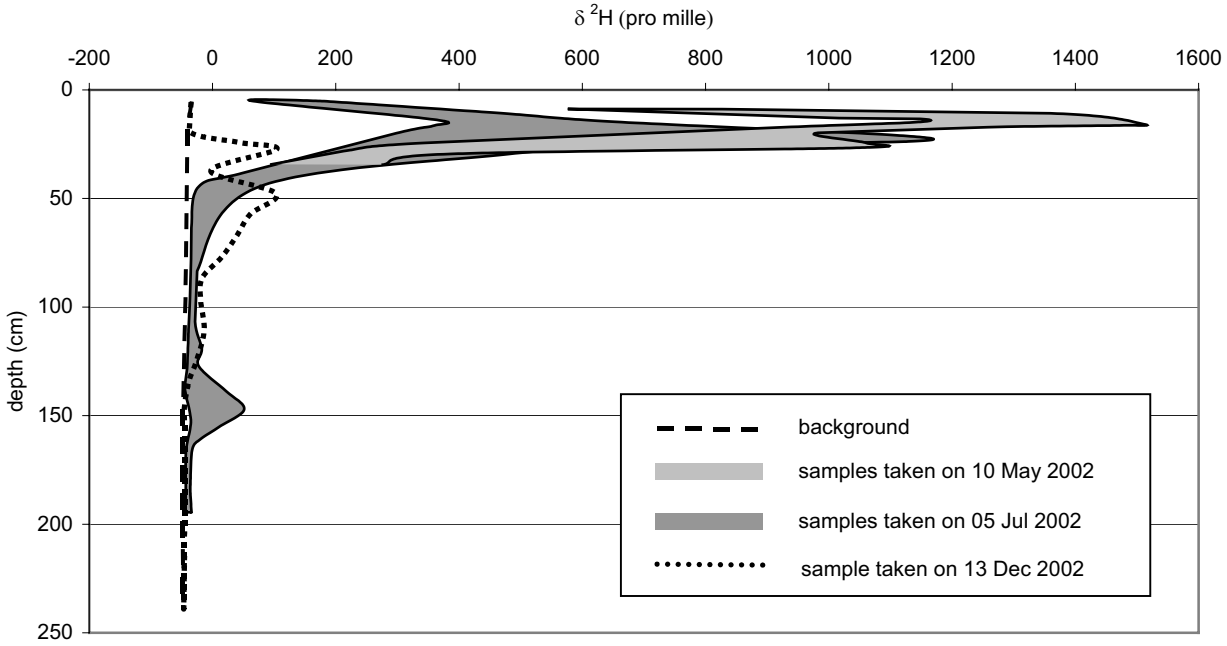

Figure 3. Deuterium concentration profiles from the Fleam Dyke site for three sampling dates in 2002

METHODOLOGY

The Fleam Dyke lysimeter consists of a 5 m cube of undisturbed Chalk, contained such that drainage water can be collected (Kitching and Shearer 1982). On top of the Chalk lies about 25 cm of sandy silt loam covered with grass. The drainage at a depth of 5 metres is led through a sloping trough, and recorded by a tipping-bucket gauge underneath (fig.2).

A tracer solution of deuterium and bromide was applied in February 2002, both on the lysimeter surface (5x5 m) and on an adjacent 4x4 m plot. The total depth of irrigated water was 1 mm and afterwards the site was exposed to natural precipitation and evapotranspiration. Following the tracer irrigation, samples of the lysimeter drainage were taken every hour, and the sampling frequency was gradually reduced to once a day as the experiment went on. To look at the vertical tracer distribution, cores were drilled on a 4x4 m plot adjacent to the lysimeter, and concurrently cores were drilled on the same site outside the tracer-irrigated area to determine the tracer background concentrations in the profile. For deuterium analyses, water was extracted from the soil and chalk samples by azeotropic distillation with toluene in a 'Dean-Stark' apparatus (Revesz and Woods 1990), and then deuterium was measured with a mass spectrometer at the British Geological Survey. For bromide extraction, the soil and chalk samples were first oven-dried and then stirred for 18 hours in ultra-pure water, centrifuged, and filtered. The bromide concentrations were measured by ion chromatography.

RESULTS AND DISCUSSION

The recordings of rainfall and drainage from the lysimeter showed that the two recharge seasons covering the tracer test were fairly average, with no recharge occurring at all between June and November 2002. For a whole year following the tracer irrigation in February 2002, the tracer concentrations in the lysimeter drainage never rose above their background values (35 µg/L for bromide and a δ-value of –45 ‰ for deuterium). While analysing the distribution of the bromide tracer in the soil and chalk samples obtained from core drilling, a problem was encountered with the natural background of bromide. The concentrations in the soil and rock samples from the background cores were so high (up to 10 mg/L), that they masked the applied bromide in the tracer profiles, thus invalidating any statement about the bromide tracer distribution. This high bromide background wasn't anticipated and is not well understood. The deuterium background, however, is very constant and the core profiles show a clear deuterium tracer distribution (fig.3). Most of the deuterium was lost to the atmosphere by evapotranspiration: by May, July and December 2002, the fractions of the applied deuterium that were recovered in the core profiles were only 9%, 5% and 1.4% respectively. Of the recovered deuterium, the majority was retained within the upper soil layers and the weathered chalk underneath, but some secondary peaks of tracer were present down to 1.5m depth.

The core profiles show high variability between individual core profiles, illustrating strong lateral heterogeneity of the flow and transport process. Most of the tracer appeared to move in a piston-like pattern, suggesting that the matrix was the dominant pathway. However, the appearance of secondary peaks deeper down the profile implies that bypass flow through the fractures must have occurred as well. Yet the abscence of tracer in the lysimeter drainage suggests that the fractrure flow did not provide a continuous pathway from the ground surface to the lysimeter base (cfr. fig.1d), or the fracture flow was such that eventually all of the tracer diffused from the fractures into the matrix (cfr. fig.1c). The secondary peak at 1.5 m in fig. 3 coincides with a hard band in the chalk profile, containing significantly less fractures. Hence the peak might be explained by bypass flow of deuterium through higher fractures and subsequent diffusion into the matrix where the fractures close.

REFERENCES

Barker JA, Foster SSD (1981) A Diffusion Exchange Model for Solute Movement in Fissured Porous Rock. Quarterly Journal of Engineering Geology 14(1):17-24

Kitching R, Shearer TR (1982) Construction and Operation of a Large Undisturbed Lysimeter to Measure Recharge to the Chalk Aquifer, England. Journal of Hydrology 58(3-4):267-277

Price M, Low RG, McCann C (2000) Mechanisms of water storage and flow in the unsaturated zone of the Chalk aquifer. Journal of Hydrology 233(1-4):54-71

Revesz K, Woods PH (1990) A method to extract soil water for stable isotope analysis. Journal of Hydrology 115:397-406

A new solution for step-drawdown tests, including flow dimension and elasticity

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A b s t r a c t : The drawdowns in most of the boreholes drilled in fractured-rocks in South Africa are not only influenced by the peculiar geometry of the aquifers (i.e. flow dimension), but also the non-linear deformation of the aquifers during the pumping of a borehole as well the dewatering of discrete fractures during the step drawdown or constant rate test.
The two new non-linear models for the analysis of step-drawdown and multi-rate tests introduced here, tries to account for these factors, in particular the deformation of the aquifer, flow dimension and dewatering of discrete fractures.

INTRODUCTION

Step drawdown and multirate tests present convenient tools for the estimation of the long-term yield of boreholes. However, the analytical methods commonly employed for the analysis of such tests are all based on the assumption that the drawdown in a borehole is a linear function of the discharge rate. Numerous constant rate tests, have shown that this is not necessarily the case with boreholes drilled in the fractured formations of South Africa. The drawdowns in these boreholes are not only influenced by the peculiar geometry of the aquifers, but also the non-linear deformation of the aquifers during the pumping of a borehole. The two new non-linear models for the analysis of step drawdown and multirate tests introduced in this paper. Although the model proposed for multirate tests is still based on constant time steps, the one for step drawdown tests allows the user to use arbitrary time steps, when performing the test in the field.

BACKGROUND

The Karoo Supergroup

Karoo formations, which underlie approximately 50% of the country, consist mainly of sandstones, mudstones, shales and siltstones. The isostatic uplift of Karoo sediments and the intrusion of Drakensberg lavas and dolerites have fractured these formations, particularly the sandstone layers that are less elastic than the rest of the rocks in the Supergroup. Karoo aquifers therefore normally contain one (sometimes a few) bedding parallel fracture, as illustrated in Fig.1, that serves as the main conduit of water for boreholes in the aquifers.

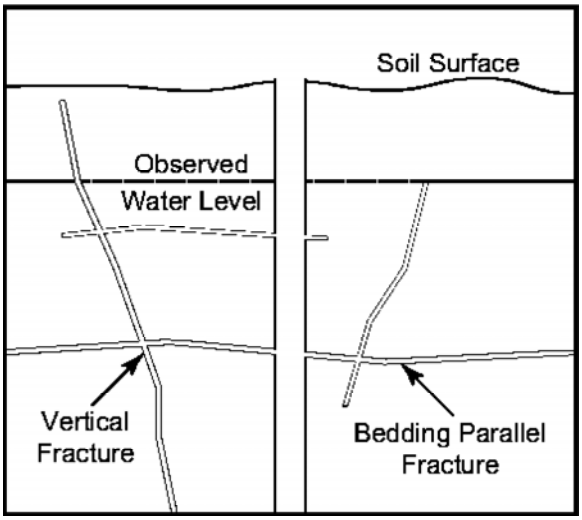

Figure 1. Schematical cross-section through a typical Karoo aquifer

The drawdown observed during a constant rate test on such a borehole consequently displays a completely different behaviour than the drawdown in a conventional borehole. If borehole storage is neglected, the drawdown initially follows a linear trend, as shown in Fig.2, which suggests that the borehole receives its water from the bedding plane fracture. This period is followed by one in which the flow is bilinear, when the borehole receives water from both the fracture and the rock matrix. Although the water level at first continue to decrease during this period, it ultimately tends to stabilise on or just above the bedding parallel fracture, provided that the discharge rate of the borehole does not exceed the rate at which the matrix can recharge the fracture. Otherwise, the water level will begin to decline again and stabilizes above another fracture (if one is present), or simply drop to the pump intake. The drawdowns observed in Karoo boreholes therefore depend not only on the discharge rates of the boreholes, but also on the geometry of the aquifer.

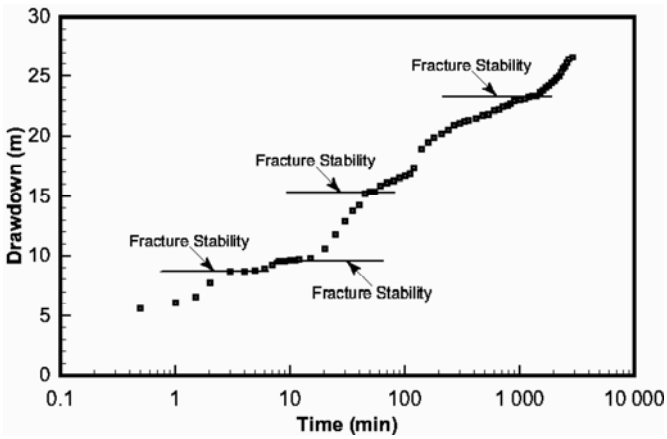

Figure 2. The drawdown observed during a constant rate test on a borehole in the Karoo Supergroup pumped at a constant rate of 15 L/s

Step drawdown tests

Step drawdown tests were introduced by Jacob (1947) to study the influence that the discharge rate, Q, has on the drawdown, s(r, t), of the water level in a borehole. His conclusion, was that the observed drawdown consists of two components—one linear in Q and the other one non-linear. He also showed that the linear component can be divided into what he called 'the linear aquifer loss coefficient', which he denoted by the symbol $B_1(r_w, t)$, and a 'linear well loss coefficient, B_2, caused by the loss of energy in the borehole itself. The former of these components can be viewed as the drawdown one would observe if water could be withdrawn from an aquifer without the loss of energy represented by the term B_2. In other words, $B_1(r_w, t)$ can be interpreted as the theoretical solution of the groundwater flow equation for the actual, physical aquifer. It is consequently impossible (at least at this moment) to distinguish between the two linear losses in

practice. Jacob therefore combined the two terms into the linear loss coefficient, defined by the equation

$$B(r_e,t) = B_1(r_w,t) + B_2$$

where r_e is known as the effective radius of a borehole, with physical radius r_w.

Jacob defined r_e as the radial distance from the vertical axis of the borehole to a point where the water level in the aquifer equals the water level in the borehole. This interpretation led him to describe the observed drawdown in a pumped borehole, s_w, with the equation

$$s_w = B(r_e,t)Q + CQ^2 \quad (1)$$

where the term CQ^2 represents the non-linear losses.

The main effect of the non-linear losses is to drive the water level in the borehole down, without contributing to Q. This could not only affect the operational costs of a borehole adversely, but also cause irreparable damage to the borehole, pump and even the aquifer.

It is common practice to assume that the coefficient C in Eq. (1) is constant and attribute the existence of the term CQ^2 to turbulent flow, caused by the pump in and near the borehole (Helweg 1994). However, there are indications that the drawdown is not only a function of Q, but also the geometry of the aquifer and that this may contribute to the non-linear term in Eq. (1) and cause the parameters B and C to be time dependent. Helweg therefore suggests that Eq. (1) should be replaced by the equation

$$s = [A + B' \log(t)]Q + [C' \log(t)]Q^p \quad (2)$$

which he claims is more general than Eq. (1). However, to achieve this he assumed that the theoretical drawdown, $B_1(r_w, t)$, could be represented by the Cooper-Jacob approximation of the Theis solution for an infinite uniform aquifer. Since this assumption is not necessary in Eq. (1), the possibility exists that Eq. (1) may describe the drawdowns of boreholes in heterogeneous aquifers better than Eq. (2), if the time is kept constant.

Another consequence of Helweg's assumption is that the flow towards the borehole must be radial, which need not be the case.

APPROXIMATION OF THE DRAWDOWNS IN FRACTURED AQUIFERS

The discussion above shows that neither the Jacob or Helweg expressions in Eqs. (1) and (2) can fit the observed drawdowns of boreholes in fractured aquifers. Since it was not obvious how to include these factors into either the Jacob or Helweg equations, a heuristic approach was used to try and adjust these equations for flow in fractured aquifers.

The recent model of Cloot and Botha (2000) for a horizontal fracture suggested that one can account for the non-linear deformation by splitting the non-linear term in Jacob's equation into two parts—one accounting for the usual effects of turbulence and the other one for the deformation. The model also suggested that the contribution of non-linear deformation will be non-linearly proportional to that of turbulence and time-dependent. Jacob's equation was consequently modified to read

$$s(t) = B(r_e,t)Q + [EQ^{p+e-1} + C'Q^p] \log(t) \quad (3)$$

where the non-linear term has been replaced by the one suggested by Helweg. The exponent $p + e - 1$ in the term $EQ^{p+e-1} \log(t)$, introduced to account for non-linear deformation of the aquifer, was chosen in such a way that Eq. (3) reduces to Eq. (1) for a fixed time if there is no deformation (or no dewatering of fractures), that is $e = 1$. The choice was further motivated by the fact that the model of Cloot and Botha indicated that the drawdown will increase if the deformation tends to close the fracture ($e > 1$).

The analysis of a large number of constant rate and step drawdown tests performed on boreholes in the fractured formations have shown that Eq. (3) cannot fully account for the observed drawdowns. However, further numerical experiments indicated that this can possibly be ascribed to the fractal structure of the fractures in these aquifers and that the equation

$$s(t) = AQ + B'Q^e (\log t)^{\Gamma(n/2)} + C'Q^p \log(t) \quad (4)$$

with $\Gamma(m)$ the normal Gamma function and n Barker's fractal dimension, provides a better approximation for these aquifers.

CASE STUDY

The present discussion will therefore be concluded with just one example, the step drawdown test performed on Borehole UP16 (see Fig.3) on the Campus Test Site. This borehole intersects the bedding parallel fracture on the site at a depth of 21 m below the surface, while its rest water level at the time of the test was 13.2 m below the surface.

The coefficients determined from the fit of $s(t)$ (expressed in m), Q (expressed in m^3/d) and t (expressed in d) to Eq. (4), are listed in Tab.1. These values were used to estimate the drawdown in the borehole for a period of 2 years, such that the drawdown would not reach the position of the bedding parallel fracture, in other words s should not exceed 7.8 m (= 21 m – 13.2 m). This yielded a discharge rate of 0.5 L/s, which agrees excellently with the value of 0.48 L/s, obtained previously.

Table 1. Various parameters that describe the fit of Eq (4) to observed drawdowns in UP16

A	B	C	p	n	e
$7.5 \cdot 10^{-4}$	$4.36 \cdot 10^{-3}$	$2.88 \cdot 10^{-6}$	2.0	1.48	1.12

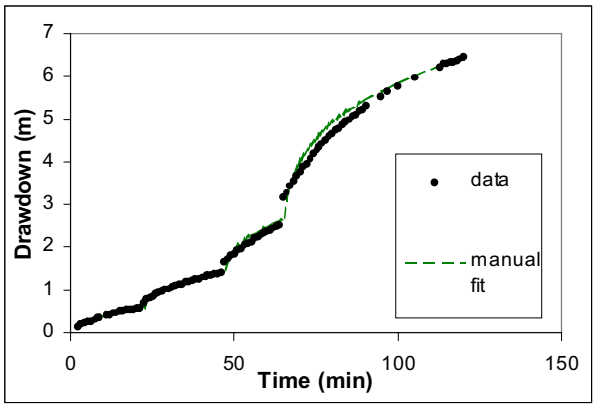

Figure 3. Fitted drawdowns compared to observed drawdowns in UP16

CONCLUSIONS

Drawdown tests are frequently the only tool available with which to assign sustainable yields for boreholes. Unfortunately, the drawdown curves in these boreholes regularly display a non-linear behaviour that cannot be attributed to turbulent effects in the borehole alone. New generalised equations were therefore derived in this to analyse step drawdown test data in these aquifers.

Non-linearities in drawdown curves should always be treated with caution, especially when used to assign sustainable yields for boreholes. This applies, in particular, to the extrapolation of the results into domains not covered during the test. Therefore, the yield estimated from this analysis should be monitored for some time after the borehole is used for production purposes.

REFERENCES

Cloot AHJ, Botha JF (2000) Modelling groundwater flow in an elastic, confined aquifer. Draft report to the Water Research Commission. Institute for Groundwater Studies, University of the Free State, PO Box 339, Bloemfontein, 9300

Helweg OJ (1994) A general solution to the step-drawdown test. Groundwater 32(3)

Jacob CE (1947) Drawdown test to determine effective radium of artesian well. American Society of Civil Engineers, Transactions, Paper 2321

Use of electrical borehole measurements for determination of fracture parameters

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A b s t r a c t : For fracture detection there are different tools and methods developed in petroleum exploration. Geophysical borehole measurement methods were investigated and those suitable for the characterisation of fracture parameters and determination of hydraulic properties in fractured aquifers were chosen. New imaging technologies, such as the Formation MicroScanner and Formation MicroImager, can yield data to determine fracture porosity, aperture and dip of fractures, but these measurements and their evaluation are expensive in comparison to other measurements. Furthermore, the data evaluation requires special knowledge and specific hardware and software. Therefore, the choice was made in favour of the Dual Laterolog tool, which is used in the development of deep thermal water routinely and makes it possible to estimate fracture parameters in hard rocks quantitatively as well. By using the Dual Laterolog, based on resistivity anomalies and separation between shallow and deep laterolog and on mud conductivity, fracture zones can be detected in addition to the fracture porosity, and the fracture aperture can be estimated easily.

ESTIMATION OF FRACTURED PARAMETERS

Due to the inverse relationship between resistivity and porosity, the Dual Laterolog (Western Atlas 1995) can be used to compute the porosity of rocks according to Archie's equation (Archie 1942), which can be applied if the sediments or rocks do not contain any clay or if the contribution of surface conduction to the signal is negligible. Fracture porosity can be estimated from the separation between the deep and shallow measurements based on the observation that the former is sensitive to the presence of horizontal conductive features only, while the latter responds to both horizontal and vertical conductive structures.

Fracture porosity

The first equation for the estimation of total porosity based on measurements of core data was developed by Archie (1942). He has found a power function, which yields the total porosity of the formation depending on the relationship between the resistivity of the formation and the formation water:

$$\Phi_{tot}^{m} = \frac{a \cdot R_W}{R_0} \qquad (1)$$

where Φ_{tot} is the total porosity, R_W is the formation water resistivity (Ωm), R_0 is the resistivity of a non-shaly formation rock (Ωm), *a* is a dimensionsless parameter (mostly about 1), m is Archie´s cementation exponent.

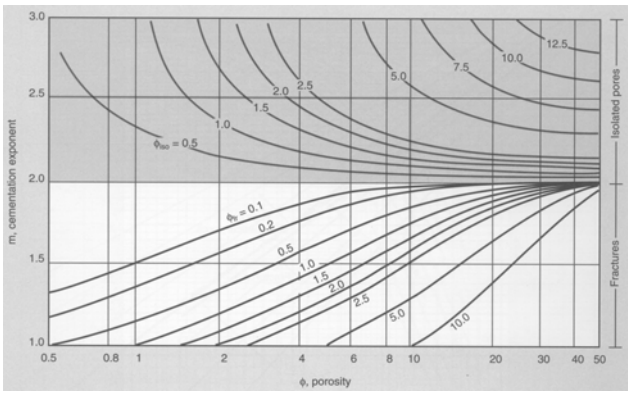

Figure 1. Chart to estimate isolated and fracture porosity (after Schlumberger 1998)

Using charts published by Schlumberger (1998), the total porosity in fractured media can be reduced to the fracture porosity, $\Phi_{frac} = f(\Phi_{tot}, m)$. If a value of m is available, the chart can be used to estimate the portion of fracture porosity of the measured total porosity (Fig.1). The graphs in the chart can be approximated well by power functions, which were determined and used at numerical calculations. Fractured formations generally have a cementation exponent less than 2. Rule-of-thumb values of m quoted in the log analysis literature for various pore systems are given in Tab.1.

Table 1. Cementation exponents for various pore systems (after John 1999)

pore system	m
intergranular/intercrystalline	2.0
Fractures	1.4
vugs	2.3
moldic	>3

In order to estimate the fracture porosity in hard carbonate formations, Boyeldieu and Winchester (1982) developed Archie´s equation further and worked out the following equation:

$$\Phi_{frac}^{m_{frac}} = \frac{C_{LLs} - C_{LLd}}{C_m} \qquad (2)$$

where Φ_{frac} is the fracture porosity, m_{frac} is Archie´s cementation exponent (usually around 1.4), C_{LLs} is the conductivity measured by the shallow laterolog, $1/R_{LLs}$ (S/m), C_{LLd} is the conductivity measured by the deep laterolog, $1/R_{LLd}$ (S/m), C_m is the mud conductivity measured by mud log, $1/R_m$ (S/m).

Fracture aperture

In fractured rocks, large separations are observed between shallow and deep laterolog curves. In high-contrast formations, the Dual Laterolog response is controlled by the resistivity of the formation blocks R_b, the resistivity of the invading fluid R_m, the extent of invasion and the fracture opening. With a few simplifying assumptions Sibbit and Faivre (1985) developed a numerical finite-element model for the Dual Laterolog measurement in a borehole in order to solve the inverse problem and to determine the fracture aperture. For modeling, a resistivity contrast of $R_b/R_m > 10^4$ was assumed. Two cases were distinguished: horizontal and vertical fractures. Qualitatively, however, it was established that horizontal behavior is dominant for angles up to 60° with the horizontal and vertical behavior for angles in excess of 75°. The model calculations resulted in the equation for long vertical fractures:

$$\varepsilon_v = \frac{C_{LLs} - C_{LLd}}{4 \times 10^{-4} \cdot C_m} \qquad (3)$$

where ε_v is the fracture aperture of vertical fractures (mm), further variables see above.

For horizontal fractures, the following formula was dereived:

$$\varepsilon_h = \frac{C_{LLd} - C_b}{1.2 \times 10^{-4} \cdot C_m} \qquad (4)$$

where ε_h is the fracture aperture of horizontal fractures (mm); C_b is the conductivity of the non-fractured host rock (S/m); further variables see above.

In addition, the authors have discovered that isolated horizontal fractures can be identified by a sharp decrease in resistivity with a total width at the inflection points of around 0.8 m and DLL possibly showing negative separation.

In the equations (2), (3) and (4), the variables C_{LLs} ($1/R_{LLs}$) and C_{LLs} ($1/R_{LLd}$) are measured directly by Dual Laterolog. C_m ($1/R_m$) is taken from the mud log measured in the borehole. In thermal water wells the borehole is mostly filled by water or a weak mix of water and mud. R_W is measured as a log with the temperature or calculated by means of a measured value and the temperature log. The formation water resistivity may be calculated from its laboratory temperature to any formation temperature and therefore for the overall borehole by Arp´s empirical formula (Arps 1953).

C_b, the conductivity of the non-fractured host rock is calculated from R_b, which may be different from R_t, the overall resistivity of the formation. In zones of non-fractured rock, the values of R_b can be replaced by the maximum values of R_{LLd}.

COMPARISON OF THE DIFFERENT RESULTS

In Tab.2 the transmissivities calculated by total-well production tests and the fracture parameters of the investigated aquifers are summarized. The values of fracture porosity represent mean values after Archie and Boyeldieu and Winchester characterizing the aquifer sections in the wells. In the case of fresh water aquifers, the ratio of conductivities falls out of range of the given criterion. Therefore, fracture apertures had to be estimated by empirical calibration of the equation (4) to get plausible values. To control the estimated fracture openings, the most common model for flow in a single fracture, the cubic law, in which the fracture is represented by two parallel plates separated by a constant distance b, was used (Bear 1993).

Table 2. Transmissivities and fracture parameters

Well	Rock type	max. R_b/R_m	T (m^2/s)	Φ_{frac} (-)	$\overline{\varepsilon}_h$ (mm) by eq. (4)	d_{frac} (1/m)	b (mm) by cubic law
Längenfeld Th2	cristalline	$4.00 \cdot 10^3$	$8.54 \cdot 10^{-5}$	0.042	22.8	1.8	$1.2 \cdot 10^{-1}$
Gabelhofen Th1	carbonate	$1.07 \cdot 10^5$	$2.32 \cdot 10^{-6}$	0.006	3.3	1.8	$2.0 \cdot 10^{-2}$
Bad Schönau IV	cristalline	$1.75 \cdot 10^4$	$4.29 \cdot 10^{-7}$	0.103	11.5	9.0	$5.5 \cdot 10^{-2}$
Gleichenberg Th1	volcanic	$4.47 \cdot 10^4$	$7.35 \cdot 10^{-6}$	0.059	6.0	9.8	$8.8 \cdot 10^{-3}$

The differences in the fracture apertures, which amount to about two orders of magnitude, can be explained as follows: The calculation by the parallel plate model results in an effective hydraulic aperture, whereby a constant distance between the fractures and parallel and smooth fracture surfaces is assumed. The flow conditions in the fractures are laminar. The field of validity of the parallel plate model is limited for fractures in which fracture roughness is small in comparison to the mean aperture. The hydraulics of fractures weathered by chemical and hydrothermal processes or filled by minerals can not be reproduced by conventional parallel plate models. The roughness of the fracture surface and the ratio of the contact area of asperities to the total fracture area were unknown and this is why they could not be taken into account.

Furthermore, the applicability of equation (4) requires a resistivity contrast of $R_b/R_m > 10^4$. The resistivity contrast exceeds 10^4 only in only few sections of the aquifers. The estimate of R_b, which cannot be directly measured by DLL and it is derived from the maximum resistivity values between fractures zones, influences the results quite considerably.

CONCLUSION

For the first estimation of fracture porosity calculated for water bearing horizons, the cementation exponent of 1.4 in equation (2) yields values in a plausible field. But the investigations show that the exponent can range from 1.1 to 1.7 at similar rocks and fracture systems. The exponent can be adjusted by core samples and it is valid only for the rock in the well. In practice, the application of equations (1) and (2) is recommended to estimate the fracture porosity of fractured aquifers with high accuracy.

The conditions assumed at the derivation of the equations (3) and (4) for hydrocarbon differ from those for water bearing horizons. A resistivity contrast $R_b/R_m > 10^4$ between mud and un-fractured host rock must also be given. This is why the fracture apertures, especially of horizontal fractures in low resistivity rocks, are calculated too high. However, the determining factor for the calculation is the resistivity contrast. By means of laboratory measurement on cores, empirical adjustment of the equations seems to be possible by modification of the constants. However, this requires further investigations by numerical modeling.

Since the constants in equations need to be adjusted so drastically to match the data, the question arises: How can the technique have a predictive value? Further investigations into high resistivity formations will be required to test the applicability and the validity of the methods for estimating the fracture aperture in fresh water aquifers.

REFERENCES

Archie G (1942) The electrical resistivity log as an aid in determining some reservoir characteristics. Trans AIME, 146:54-62

Arps J.J (1953) The effect of temperature on the electrical resistivity of sodium chloride solutions. Journ Petrol Technol Techn Note 175:17-20

Bear J (1993) Modeling Flow and Contaminant Transport in Fractured Rocks. In: Bear J, Tsang C-F, Marsily G (ed.) Flow and Contaminant Transport in Fractured Rock. 1:1-37

Boyeldieu C, Winchester A (1982) Use of the Dual Laterolog for the Evaluation of the Fracture Porosity in Hard Carbonate Formations. Offshore South East Asia Conference, Singapore

John H (1999) Basics of Oil and Gas Log Analysis. Kansas Geological Survey, Doveton

Schlumberger (1998) Log Interpretation Charts. Schlumberger Wireline & Testing, SMP-7006, Sugar Land, Texas

Sibbit AM, Faivre O (1985) The Dual Laterolog Response in Fractured Rocks. Trans, paper T, SPWLA 26th Annual Logging Symposium, 1-34

Western Atlas (1995) Introduction to Wireline Log Analysis. Western Atlas International Inc., Houston, Texas

Experiments on flow and transport processes in fractured porous media in dependence on fracture and rock permeability

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A b s t r a c t : Due to the complex interaction of numerous coefficients, the reliable prediction of hydraulic circumstances and mass transport within fractured porous media proves to be complicated. Besides the significant scale-dependence of flow and transport parameters primarily the combination of structure geological aquifer information and empirically determined, process-based information represents a fundamental aspect for aquifer characterisation.
By dint of the aquifer analogue approach a description of hydraulic circumstances and mass broadening within porous fractured aquifers becomes possible at certain ranges of scale. A spatial limited, representative area of the natural aquifer is excavated and prepared for multi-directional tracer tests applying gas- (unsaturated) and fluid-tracers (saturated). Furthermore a detailed deterministic and/or stochastically generated model of the aquifer area can be developed by statistical ascertainment of structural data. The choice of suitable experimental setups allows investigations on tracer-specific particularities, the influence of changing boundary conditions, questions of fracture-matrix-interactions and the applicability of different mathematical models.

METHOD

Flow and transport processes in fractured porous aquifers are influenced not only by the fractures orientation and properties but also by both diffusive and sorptive interactions between joints and matrix and inside the matrix. Tracer experiments in a sealed natural system with statistically analysed fracture distribution and lab-examined matrix characteristics make a direct measurement of fracture- and matrix-caused influences on transport processes possible. It is one of the most significant problems to transfer determined transportation parameters from lab- to field-scale. This upscaling-problem shell be solved by carrying out tracer tests at an aquifer analogue, an intensively investigated in situ sandstone test boulder of about 200 m³ size. By statistical evaluation of the investigated fracture distribution and by stereophotogrammetric shooting of the block surface and side walls it is possible to generate a partly deterministic, partly stochastic 3D-model of the test site. Thus flow and transport parameters, measured in He and SF_6 gas tracer tests, can be worked up by both analytical and numerical models.

Choosing a symmetric set-up of tracer injection and detection borings in the central area of the test site, helps to minimise inaccuracies caused by the boulder edges. The development of pressure and tracer concentration during the tests can be determined at nearly any point of the aquifer analogue by installing a grid of 74 control ports.

By bringing up a complete concrete-coating on the surface and the side walls, the aquifer analogue can be saturated. Now it is possible to carry out aquatic tracer tests in saturated porous fractured media analogues to the gas tracer tests. By this the transfer of pneumatically determined transport parameters to flow processes in the saturated system can be judged.

THE TEST SITE

Two criteria had to be met while searching for a suitable location of the test site to set up in context of the hard rock aquifer analogue project. On the one hand matrix porosity of the rock had to be exceptional high, on the other hand the material should be fractured densely and as homogeneously as possible. Infrastructural considerations had to be kept in mind, too. Concerning the provided excavation and the instrumental extension of the test site the existence of bus bar and water supply is recommendable. Due to the intended construction works also a sufficient access road should be set up. Thus the search was concentrated on quarries in middle- or Upper Triassic sandstones of middle or southern Germany.

At last the in situ hard rock test site is located at the edge of a sandstone quarry 25 km south of the city of Stuttgart in the state of Baden-Württemberg/Germany. The rock material is of very porous, densely fractured so called “Stuben”-sandstone of Upper Triassic age. The porosity was determined by mercury porosimetry on core samples to vary from about 14 % to 22 %. The test site is roughly 10 m – 8 m – 2 m in size (fig.1). It was sealed off from its environment by a concrete coating, covering both horizontal and vertical surfaces.

While fixing the exact test site boundaries, information gained of former quarry investigation borings could be implemented. Borings in the north-eastern part of the quarry area indicated a thickness of the top sandstone layer from 2.2 m to 2.5 m. After further verification of the expected sandstone thickness by four core drillings, an area of about 10 m – 10 m was assigned for setting up the test site within the top sandstone layer.

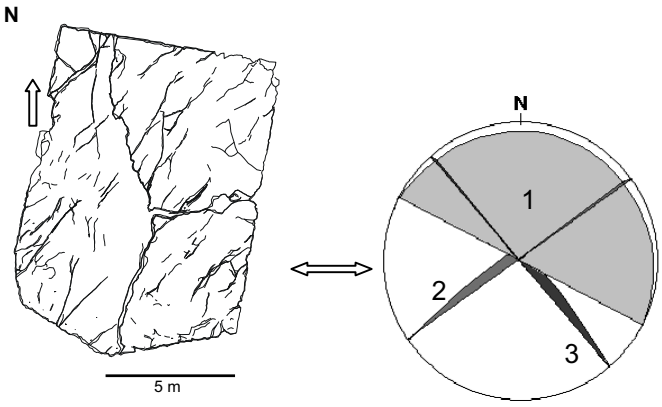

Figure 1. Test block surface (left) and main fracture orientation (right)

FRACTURE PARAMETERS

About 300 fractures have been recorded at the test site, using the scanline method. After assigning favoured orientations among this huge amount of fractures, those elements with its orientation not exceeding a certain angle of selection are centralised to clusters. Every single cluster is representing a main fracture orientation to which properties as aperture or fracture length can be statistically assigned. In this manner a statistical model of the test side can be generated.

At test site Pliezhausen also another, less labour intensive kind of fracture registration was used. The stereophotogrammetric shooting is mainly working with a stereometric camera and an analytic plotter. Initially photographs are taken from all over the test block, using the stereometric camera. Then fracture lines, visible in the stereo-pictures, are analysed by an analytic plotter. In Pliezhausen all together five walls could be used for stereophotogrammetric fracture orientation evaluation. Among these were two side walls of the raw test block and four quarry mining walls, partly orthogonal oriented. The stereo pictures have been analysed by the department of photogrammetry and remote sensing at Karlsruhe University.

Orientation of the discontinuities are plotted as contoured area plots of the discontinuity normals in the lower hemisphere using the cosine-exponent-weighting-method (Adam 1989). Clusters of preferred orientations are determined by identifying the peak discontinuity densities and choosing an appropriate selection angle for each cluster (Witthüser *et al.* 1998). The identified clusters are assumed to satisfy a Fisher distribution. Every cluster can be associated with statistically evaluated geological characteristics. Tab.1 gives a brief overview of the three main clusters and their spherical apertures.

Table 1. Normal orientation of main discontinuity planes with spherical aperture of each cluster (Witthüser 1998)

cluster	dip direction	dip	spherical aperture
1	201°	85°	11.22°
2	146°	7°	12.05°
3	229°	8°	10.20°

TRACER TESTS

In order to achieve information about flow- and transport-parameters of fractured porous media, tracer tests with gas tracers are set up in the unsaturated field test block. This method bases on the experimental inducement of a transport process over a certain distance in an artificial flow field within the aquifer to be investigated. Thus empirical data can be compared to different analytical solutions of the differential equations, describing the transport process.

For executing the experiments, some drillings are made at the test block, which can be used as points of injection resp. extraction. By detracting a constant stream of air at one of these holes, low pressure can be generated inside the test block. To open one of the other air-tight locked holes makes a flow of air stream into the otherwise sealed system. By doing so a constant flow field will be installed from one boring to the other inside the porous fissured aquifer after a specific period of time. Certain ranges of depth within the borings can be tested separately when using a packer system.

In Pliezhausen helium and sulfur hexa fluoride are used as tracer gases. Impulses of these gases are pressureless injected into the injection boring while recording the time-depending change of concentration within the air, taken out of the extraction boring. In that way recorded tracer brake through curves can then be adapted by the general transport equation (Lever *et al*. 1985 and Tang *et al.* 1981) for two-dimensional transport of water solluted material in a single fracture, caused by a radial convergent flow field. This equation can be solved, using the advection-dispersion-model (ADM) (Lenda and Zuber 1974) or the single-fissure-dispersion-model (SFDM) (Maloszewski and Zuber 1990).

By an iterative adaption of these equations to the experimental evaluated tracer brake-through-curves (BTCs), transport in a natural aquifer system can be described approximately, using the fitparameters peclet number *Pe*, mean transit time t_0 and diffusion-parameter *a*. The best adaption to the tracer brake through, measured at the test block by Thüringer (2001) can be achieved by a combination of ADM and SFDM. As increase and peak area can be described best by ADM, decrease and tailing show the best fitting results when applying SFDM (fig.2).

Table 2. Analytically determined fit parameters of gas tracer tests using He and SF_g for both ADM and SFDM

		t_0 [min]	Pe	α_L [m]	a
He	ADM	7.6	13.1	0.15	-
	SFDM	5.9	30.7	0.06	0.011
SF_6	ADM	11.5	4.8	0.40	-
	SFDM	5.4	31	0.06	0.025

This composition clarifies the main differences between ADM and SFDM. As the ADM describes transport only by advective and dispersive processes, the SFDM also implements diffusion-caused retardation by the introduction of the diffusion parameter *a*. Thus the dispersive part of the tailing decreases and the peclet-number increases, applying the SFDM (tab.2).

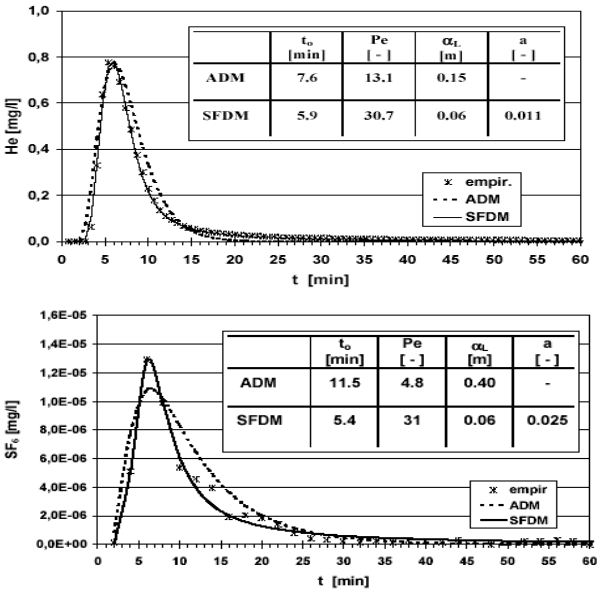

Figure 2. Experimental tracer-BTCs and adaption by ADM and SFDM using helium (top) and SF_6 (bottom) as tracer gas; (Thüringer 2002)

REFERENCES

Adam JF (1989) Methoden und Algorithmen zur Verwaltung und Analyse axialer 3-D-Richtungsdaten und ihrer Belegungsdichte. Göttinger Arbeiten zur Geologie und Paläontologie 40:100 pp

Lenda, Zuber (1974) Tracer dispersion in groundwater experiments. Isotope techniques in groundwater hydrology, Vol. II; IAEA-SM-129/7:619–641

Lever *et al.* (1985) The effect of dead-end porosity on rock matrix-diffusion. J Hydrol 80:45-76

Maloszewski, Zuber (1990) Mathematical Modeling of Tracer Behavior in Short-Term Experiments in Fissured Rocks. Water Resour Res 26(7):1517–1528

Thüringer Ch (2002) Untersuchungen zum Gastransport im ungesättigten, geklüftet-porösen Festgestein Diss Univ Karlsruhe, Karlsruhe (online available), 128 pp

Witthüser K, Himmelsbach Th (1998) Erhebungsmethoden von Kluftparametern für eine stochastische Kluftnetzgenerierung. Grundwasser 3(3):10 3–106

GIS - supported evaluation of groundwater yield in the fractured rocks of the Rhenish Massif, Germany

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Abstract: In a study at the Department of Engineering Geology and Hydrogeology a GIS-supported method based on hydrogeological parameters for the evaluation of groundwater yield called "HYPA" has been developed. The method is applied in the context of the elaboration of groundwater vulnerability maps scaled 1:25,000 for the Ministry of Environment of North Rhine-Westphalia (Wimmer *et al*. 2001, Wimmer *et al*. 2002). The main parameter used by the HYPA method is represented by the permeability of hardrocks. This information is available for the whole working area of the Rhenish slate mountains in form of hydrogeological maps. The relationship between permeability of hard rocks and the groundwater yield has been established by analysing the behaviour of discharge of several thousand small rivers and beeks according to the lithology of outcropping hardrocks in their catchment areas. The amount of precipitation as well as thicker softrock overburden and impermeabilisation due to human impact represent the main boundary conditions for the applicability of he HYPA Method.

THE HYPA METHOD

The HyPa method relies on the relationship between groundwater recharge and permeability of hard rocks.

To verify the applicability of this approach for the Rhenish Massif, two study areas with differing hydrogeological characteristics have been considered. The method was first developed for the Bergisch Gladbach-Paffrath Syncline with its high hydrogeological complexity of karst aquifers and then applied in the fractured aquifer in the area of Kronenburg (fig.1).

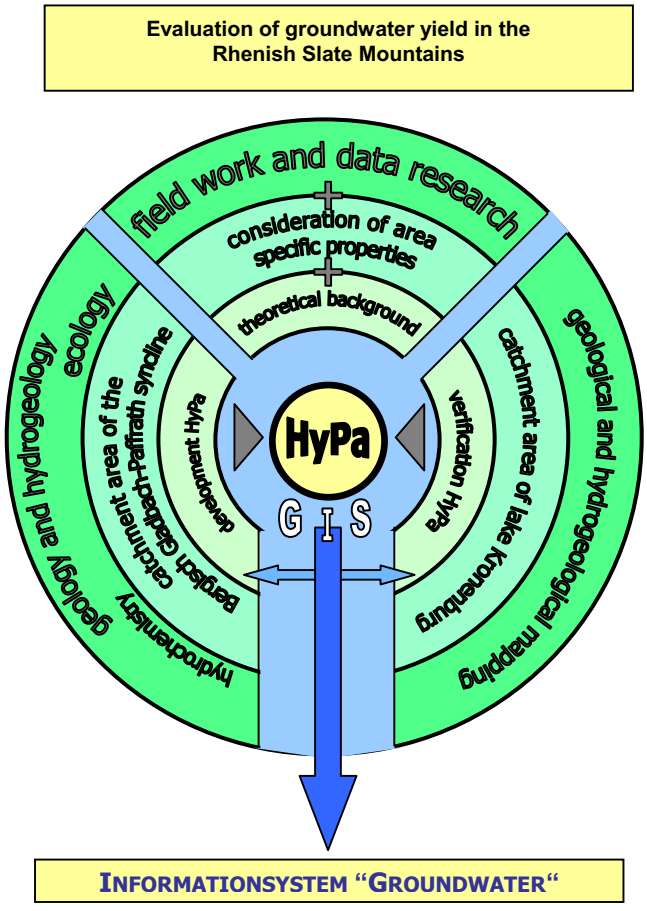

Figure 1. Development and calibration of the HyPa method

The results have been compared to the assessment of groundwater yield by water balance considering precipitation, evapotranspiration and discharge, also GIS-supported. They differ by approximatively 6% for the considered catchment areas. Several methods for evaluating the evapotranspiration for the study area in the Bergisch Gladbach-Paffrath Syncline aided by GIS have been applied. Preference is given to the Method according to Renger and Wessolek (1996) which takes into account landuse as well as soil properties.

Emphasis has been put on the interpretation of precipitation data, as well as different methods of discharge measurement. The results of precipitation measurements differ in relation with the exposition of the weather station. Especially wind influence during snowfall leads to mismeasurements of up to 30% of the amount of precipitation. In wind-exposed position the amount of precipitation lies about 15% higher than it is recorded by the classical measurement.

Depending on flow volume and flow regime, different methods for discharge evaluation can be recommended. In small beeks with turbulent flow regime discharge evaluation give best results by measuring the displacement of concentration peaks following a tracer input. Small amounts of salt (NaCl) can be used as tracers without the risk of polluting the environment. The results have been compared to the discharge evaluation with the help of proportional dams and show an extraordinary good fit (Wimmer 2002).

The HyPa method fits with the results obtained by groundwater yield determination, proving that the rate of groundwater recharge in the Rhenish Massif is primarily dependent on hydrogeological parameters.

A relation between hard rock conductivity and groundwater recharge is determined (fig.2). Valid ranges depend primarily on inhomogeneous permeability conditions in the vadose zone of the hard rocks.

Boundary conditions for the applicability are mainly the existence of amounts of precipitation higher than 650mm per anno as well as a thickness of soft rock overburden, that should not exceed 2.5m. For the evaluation of groundwater yield emphasis has to be put on the correct determination of the size of the corresponding catchment areas. Especially in karstified rocks this can be a major problem since catchment areas do not generally follow morphological aspects.

Sealed surfaces like villages, towns, roads etc as consequence of human influence can easily be taken into consideration with the HyPa Method if the degree of sealing is known.

USING THE HYPA METHOD

The use of the HyPa method with the help of a geographical information system consists in 6 steps. First the geology in terms of lithological composition of the outcropping hard rocks has to be examined. After determination of the exact catchment area the conductivity properties of these rocks are taken into consideration. Therefore the polygon geometries of the geological setting are attributed with the amount of groundwater recharge to be expected according to fig.2.

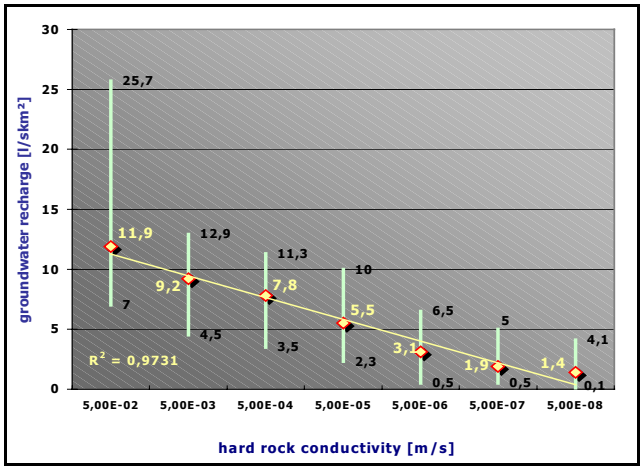

Figure 2. Relationship between annual groundwater recharge and hard rock conductivity. Valid ranges shown as vertical lines depend on inhomogeneous lithological settings as well as tectonic aspects.

The catchment area is then clipped from the surrounding geometries. This data set is then turned into a grid with a grid size of 10 by 10m. The statistical analysis of this grid shows the amount of average annual groundwater recharge per grid cell, which by multiplication with the total number of cells represents the annual average amount of groundwater recharge for the catchment area, in question (fig.2).

Sealed surfaces have to be regarded separately. They only have influence if they play a potential role in groundwater infiltration. Therefore sealed surfaces overlaying for example shales with little natural effects on groundwater recharge can be neglected. The first step consists then in clipping the sealed surfaces out of the polygon geometries attributed with the amounts of potential recharge capabilities. From these geometries only those with medium to higher infiltration capacities are taken into consideration. With the help of Hypa the theoretical amount of annual groundwater recharge under natural condition is then calculated for the reminding geometries. With the knowledge of the degree of sealing it is then easy to determine the average annual groundwater recharge for these areas and taking them into account in the global groundwater yield of the regarded catchment area.

ADVANTAGES OF THE HYPA METHOD

The main advantage of the new method is the little number of input parameters as well as their global availability. It is an easily applicable method using GIS. The primary result being a grid data set further information in different hydrogeological questions can be derived by combining various data sets. The method gives long term average results that fit well compared to classical evaluation of groundwater yield at an appropriate scale of 1:25.000. A further advantage is that it is not necessary to evaluate evapotranspiration which generally is quite complex, due to the large amount of parameters to be taken into consideration as well as their availability. Also a separation of discharge into groundwater recharge and surface runoff is not necessary. Disadvantages consist in the time invariability of the result as well as the local disregard of boundary condition regarding overlaying soft rock thickness. The method as such should also be applicable in other areas then the Rhenish Massif, as long as boundary conditions are respected.

CONCLUSION

The HyPa-method can be used for evaluating the long-term groundwater yield in the Rhenish Massif. It can be applied as a module "Groundwater yield" in the framework of the thematic information system "Groundwater" of the Ministry of Environment of North Rhine-Westphalia. It allows an effective, quantitative statement about the potential of the resource groundwater in the presented scale, for example on behalf of questions of groundwater-management. The HyPa method can be embedded in the evaluation of groundwater vulnerability in hard rock aquifers.

REFERENCES

Renger M, Wessolek G (1996) Jährliche Grundwasserneubildung in Abhängigkeit von Bodennutzung und Bodeneigenschaften. DVWK-Merkblätter zur Wasserwirtschaft: Ermittlung der Verdunstung von Land- und Wasserflächen. Merkbl. z. Wasserwirtsch 238:47

Wimmer G (2002) Ermittlung des Grundwasserdargebotes in Karst- und Kluftaquiferen des Rheinischen Schiefergebirges mit Hilfe Geografischer Informationssysteme in ausgewählten Einzugsgebieten im Raum Bergisch Gladbach und Kronenburg/Eifel. Mitteilungen Ing.-u. Hydrogeologie 82:1-380

Wimmer G, Leppig B, Hüsener D, Schetelig K (2001) Das Hydrologische Kartenwerk Nordrhein-Westfalen auf dem Weg zum Fachinformationssystem "Grundwasser". In: Strobl J, Blaschke T, Griesebner G, (eds) Angewandte Geographische Informationsverarbeitung–Beiträge zum AGIT-Symposium Salzburg 2001 XIII:524-533

Wimmer G, Leppig B, Dietz Th (2002) Die Grundwassergefährdungskarte über Locker- und Festgesteinsaquiferen–Erfahrungen bei der Umsetzung des theoretischen Modells in die Praxis. Mitteilungen Ing.-u. Hydrogeologie 80:253-272

TOPIC 5

ANTHROPOGENIC IMPACTS ON FRACTURED ENVIRONMENT

- Impacts of urbanisation and industrialisation
- Quantitative and qualitative groundwater protection
- Effect of underground constructions on groundwater: deep disposal sites, tunneling, mining; hydrogeologic interpretation of results

Isotopes as tracers in a contaminated fractured chalk aquitard

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Clusters of industrial plants often generate contaminant plumes with several potential sources. Prevention of further pollution and design of suitable remedial measures require the identification of the contributing source among all potential ones and the sorting of currently active sources from historical ones. In the study area, an industrial complex in the Negev desert, Israel, contaminants could not serve as indicators for the contamination sources because of their extensive spatial distribution across the site. However, stable isotopes of oxygen, hydrogen and sulfur, as well as tritium, proved to be an efficient tool for this task.
The isotopic characterization of the potential end members provided the criteria for constraining a contaminating source when several alternative sources appeared viable. The isotopic fractionation of oxygen and hydrogen isotopes could be tied to the various disposal phases of the industrial wastewater. The three presented case studies confirm the important role of isotopes as tracers in contaminated sites.

Effects of tunneling on the groundwater resources of the southwestern San Bernardino Mountains, California, USA

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A b s t r a c t : A 2-kilometer long, 5.6-meter diameter horizontal tunnel was constructed in the southwest San Bernardino Mountains, California, USA. Water inflows into the tunnel occurred at rates up to 0.09 m^3/s. Water levels in monitoring wells were lowered by as much as 76 m. The U.S. Geological Survey developed conceptual and numerical models to resolve questions and issues. Rock types of the area are metamorphic and igneous and the San Andreas Fault borders the southwest edge of the area. The model framework was developed using FracMan, a discrete fracture network numerical code. Flow equations were solved using MAFIC, a flow code coupled to FracMan. Mapped lineaments and faults were used to build the geologic framework. The lineaments were evaluated in terms of their spatial, length, and orientation distributions and intensity. The model was calibrated to measured values of pre- and post tunnel conditions including stream discharge, piezometers installed in the tunnel, and heads in boreholes.

INTRODUCTION

A 5-kilometer long, 5.6 meter diameter horizontal tunnel is being constructed by the Metropolitan Water District of Southern California (MWD) under U.S.D.A. Forest Service land in the southwest San Bernardino Mountains, California, USA. After tunneling approximately two kilometers, water inflows into the tunnel occurred at rates up to 0.09 m^3/s and averaged 0.031 m^3/s over 780 days. Water levels in nearby monitoring wells were lowered by as much as 76 m, and discharge rates from springs on private and federal locations were reduced. Issues identified by stakeholders in the area were:

(1) what is the spatial extent of the lost water resource and
(2) what is the recovery time to original conditions after the tunnel was lined.

Conceptual and numerical models were developed by the U.S. Geological Survey to resolve questions and issues. This progress report describes the process of analyzing the effects of ground water inflow into the constructed tunnel.

Rock types of the San Bernardino Mountains consist of predominately metamorphic and igneous rocks. The San Andreas Fault borders the southwest edge of the area and influences both local and regional structural characteristics. Subsurface water storage and transport is controlled by the complex fault and fracture system; rock matrix is not a factor.

MODEL DEVELOPMENT

From the modeling process and field observations, a generalized conceptual model was developed. The flow system is typical of mountain and valley floor terrain. That is, most of the recharge occurs in high elevations, penetrates deep into the rock mass, and discharges to stream drainages at the valley floor. The San Andreas Fault helps deflect deep ground water to surface drainages, although there is some discharge through the fault. Some recharge occurs in the area between the high elevation site and the valley floor. The area is steep with varied relief and the recharge is shallow, travels short distances, and discharges as springs.

Measured inflow into the tunnel shows that the flow comes from several discrete zones. The use of a discrete fracture network numerical model to evaluate the flow system is consistent with this observation.

The model framework was developed and evaluated using FracMan, a discrete fracture network numerical code. Mapped lineaments and faults were used to build the geologic framework. The framework part of the model covered about 8.09 x 10^8 m^2 and 5000 m deep. Lineaments were mapped from three sources: colored infrared aerial photos at 1:20,000 scale; a single colored photograph of the Arrowhead East tunnel alignment area at 1:40,000 scale; and several Digital Elevation Model maps with various views and scales. Fault orientations were taken directly from MWD's geologic map of the area. Lineaments were evaluated in terms of their spatial, length, and orientation distributions and intensity.

Spatial analysis of the lineaments determined if the lineaments are randomly spaced or clustered. Length distribution was calculated using a mass-dimension fractal method (La Pointe *et al.* 1999) and a complimentary cumulative density function of length. The analysis indicated that the minimum size was 600 meters and the maximum length was 8,000 meters.

Length distribution for mapped faults was calculated by measuring the trace length of each fault on a geologic map. The model does not generate a fault trace, but instead generates a polygon that approximates a circle. A 2-D plane is then generated that replicates the ground surface and cuts the polygon to form a line, similar to a fault trace. The radius of the polygon is adjusted so that when the plane cuts the ellipse at a similar elevation, the resulting line is the same length as the mapped fault trace. The mapped orientation and center point location of each fault was put directly into the model.

Lineament intensity was determined from the lineament map for various size areas and scales. Intensity was expressed as the number of lineaments per square meter ($\#/m^2$) and total lineament length per square meter (m/m^2). Mean and standard deviation for the number per square meter was 1.07E-05 $\#/m^2$ and 9.33E-06 $\#/m^2$, respectively, and the simulated mean value was 1.63E-06. Mean and standard deviation for the length per square meter was 4.42E-03 and 6.25E-04, respectively, and the simulated mean value was 4.50E-03. Because the intensity was similar for each area sampled, there is confidence the lineaments formed from a single source and that the different lengths are part of one population.

PARAMETERIZATION

Flow and head equations were solved using MAFIC, a flow code coupled to FracMan. Boundary conditions include two recharge sites, six stream discharge locations, the constructed part of the Arrowhead East tunnel, and four boreholes. The northern recharge site covers 7.2 x 10^7 m^2 with a simulated constant rate of 0.18 m^3/s (eight percent of precipitation) and the southern recharge area had a constant rate of 0.04 m^3/s (four percent of precipitation).

Transmissivity values of lineaments could not be measured directly; therefore, the best fit was determined by trial and error.

Because the model process is stochastic, each simulated lineament was assigned a value from a transmissivity distribution. The distribution was lognormal with a mean of 3.0E-05 m^2/s and a standard deviation of 5.0E-06 m^2/s. Transmissivity values assigned to faults also were selected by trial and error and averaged 5.0E-08 m^2/s.

MODEL CALIBRATION

Steady State. The model was calibrated to measured values of the following boundaries, under steady state or pre-tunnel conditions 1) Stream discharge; 2) 14 piezometers installed in the tunnel; and 3) Heads in boreholes. Simulated flow rates at stream discharge points were within one percent of measured. Simulated pressures of the tunnel piezometers (installed after the tunnel was lined) were within one to five percent of measured. Simulated heads in boreholes were within one to two percent of measured.

The model also calibrated to post tunnel construction. The simulated rate of inflow into the tunnel, under steady state conditions, was 0.042 m^3/s and a measured rate of 0.031 m^3/s. Because the measured rate was not considered steady state (open for 780 days), the simulated rate was expected to be greater than the measured.

Transient. The steady state model was used to initiate transient simulations. The transient part of the model was from periodic opening or the constructed part of the tunnel and subsequent flow into the tunnel. The model was calibrated to the measured drop in the heads of four boreholes and to the measured rate of inflow into the tunnel with time. Simulated head drops in boreholes were similar to measured, but need further calibration. Simulated rates of inflow into the tunnel with time were similar with the measured. The next step is to close the tunnel to inflow and calculate the time it takes for the heads in the boreholes to recover to pre tunnel values.

SUMMARY

We have constructed a geologic framework and flow numerical model for a fractured metamorphic and igneous aquifer system. The flow model was calibrated to borehole heads, base flow discharge, in situ tunnel pressure, and steady state inflow into the constructed part of a 2 kilometer long tunnel. Transient simulation of an open tunnel with time showed that heads in boreholes declined similar to measured and heads and rates of inflow into the tunnel with time were similar to measured values.

REFERENCES.

La Pointe PR, Cladoushos T, Follin S (1999) Calculation of displacements on fractures intersecting canisters induced by earthquakes: Aberg, Beberg and Ceberg examples: SKB Technical Report TR-99-03, Stockholm, Sweden, 103 pp

Identifying hydrologic/hydrogeologic impacts caused by tunnel construction

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A b s t r a c t : De-watering of the groundwater resource, and reduced flow of surface water features such as local springs and streams, is a potential negative impact when constructing tunnels. Recognizing this, prior to construction of two rock tunnels in California, a program to monitor over 100 wells, springs and streams in the project area that might be affected, was implemented. Three years of pre-construction monitoring have established data for a hydrologic reference, which indicates a high degree of spatial and temporal variability of the hydrologic features. This variability must be accounted for when trying to identify construction related impacts. Correlation of the reference period data with precipitation and other parameters was established to identify and measure potential impacts to hydrologic features. Natural hydrologic and geologic boundaries were used to sub-divide the project area into units of similar characteristics. Measurements from features within each unit were normalized and aggregated do derive a single representative flow parameter. The correlation of the representative flow to nearby precipitation and stream flow records was used to develop a means of estimating unimpacted flow and groundwater levels during and after tunnel construction. The estimates will be monitored to actual monitoring measurements during that time to assist in identifying the extend and the magnitude of potential impacts.

This paper describes an extensive program of monitoring water resources features during the construction of tunnels in a semi-arid region of the western United States. Early in the planning stages of the tunneling project it was realized that the construction, although temporary, could impact the water resources of this mountainous area. Groundwater is critical in sustaining the water sources of the flora and fauna of the area, as well as providing domestic wells. Measures to control and minimize any such impacts included pre-excavation grouting in advance of tunnel excavation, and an impermeable lining in the final design of the tunnels. Installation of the lining was planned to follow behind the advancing excavated face as close as practical to further reduce the opportunity for inflow to the tunnel. However, the tunnels are excavated in a complex of intrusives and metamorphics. The occurrence and movement of groundwater occurs primarily within fractures and the storage yield is small. It was recognized that even with the planned constraints to reduce groundwater inflow during excavation, the construction could cause measurable impact on water sources. A water-resource monitoring program was recognized as a key provision in the efforts to minimize and control any impact on the environment.

A canvass to identify all water resource features (i.e.; streams, springs, wells) in the area was initiated early in the planning of the project. Critical resources were selected to begin periodic monitoring, and sites for groundwater observation wells were selected. Monitoring well construction was an integral part of the tunnel alignment exploration. As a result of this early initiation of the monitoring program, over three years of pre-construction monitoring were collected to provide a “baseline” reference period of data, illustrating yearly and seasonal fluctuations, unaffected by construction. Those fluctuations are in response, predominantly, to precipitation, and other factors, independent of the construction. Correlation of the reference period data with precipitation and other parameters was established to identify and measure potential impacts to resource features.

Hydrologic and geologic boundaries were used to sub-divide the project area into hydrologic units of similar characteristics and resource features are identified with an appropriate unit. Measurements of surface features of each unit were normalized and aggregated do derive a single representative flow parameter. The correlation of the representative flow to nearby precipitation and stream flow records was used to develop a means of estimating unimpacted flow and groundwater levels during and after tunnel construction. The estimates were compared to actual monitoring measurements during that time to assist in identifying the extent and the magnitude of potential impacts.

Over 100 of the wells, springs and streams of the canvassed resources were selected for close monitoring during construction of the tunnels. The close monitoring is to enable timely warning for preparation of mitigation procedures, should an impact develop, and protection of the environment be needed. This program of surveying and monitoring resource features is one of the most extensive and detailed programs ever developed for controlling the impact of tunnel construction on a groundwater resource.

A three-tiered procedure was developed in order to identify construction related impacts as quickly as possible, while avoiding classifying natural fluctuations as impacts. A decision tree diagram of this procedure is presented on Figure 1. The primary objective of the first two tiers of the procedure are directed to identifying areas and features that are most likely to be impacted. The purpose is to allow effective concentration of monitoring efforts to those areas and individual features. The third tier is review of all available information at individual features to determine whether or not an impact has actually occurred.

First tier of detection (groundwater level evaluation) was directed to the monitoring wells, based on the fact that a measurable interference by tunnel construction is most likely to be first detected at the monitoring wells, and they are the closest in proximity to tunnel excavation. Features further from the tunnel or hydraulically separated from the tunnel may be impacted later, or not at all. The first tier response functions as an alert that an impact is developing and to determine the probable area that may be affected. Closer monitoring can be directed to that area.

The second tier of detection (the Hydrologic Unit level evaluation) addresses impacts to the composite flow of the hydrologic units. This second tier evaluation is used to determine whether impacts identified at the monitoring wells has progressed and is affecting springs and streams.

The third tier of detection (the individual feature evaluation) is used to identify whether individual features within each hydrologic unit are impacted. This is necessary since the methods used to combine individual features into composite hydrologic unit may obscure an impact to one or two individual features. However, because the natural fluctuation in flow at individual features is much greater than that of composite flow of the hydrologic unit, careful monitoring and field inspection was needed to establish the degree of impact. Judgment was a significant part of decisions at this tier.

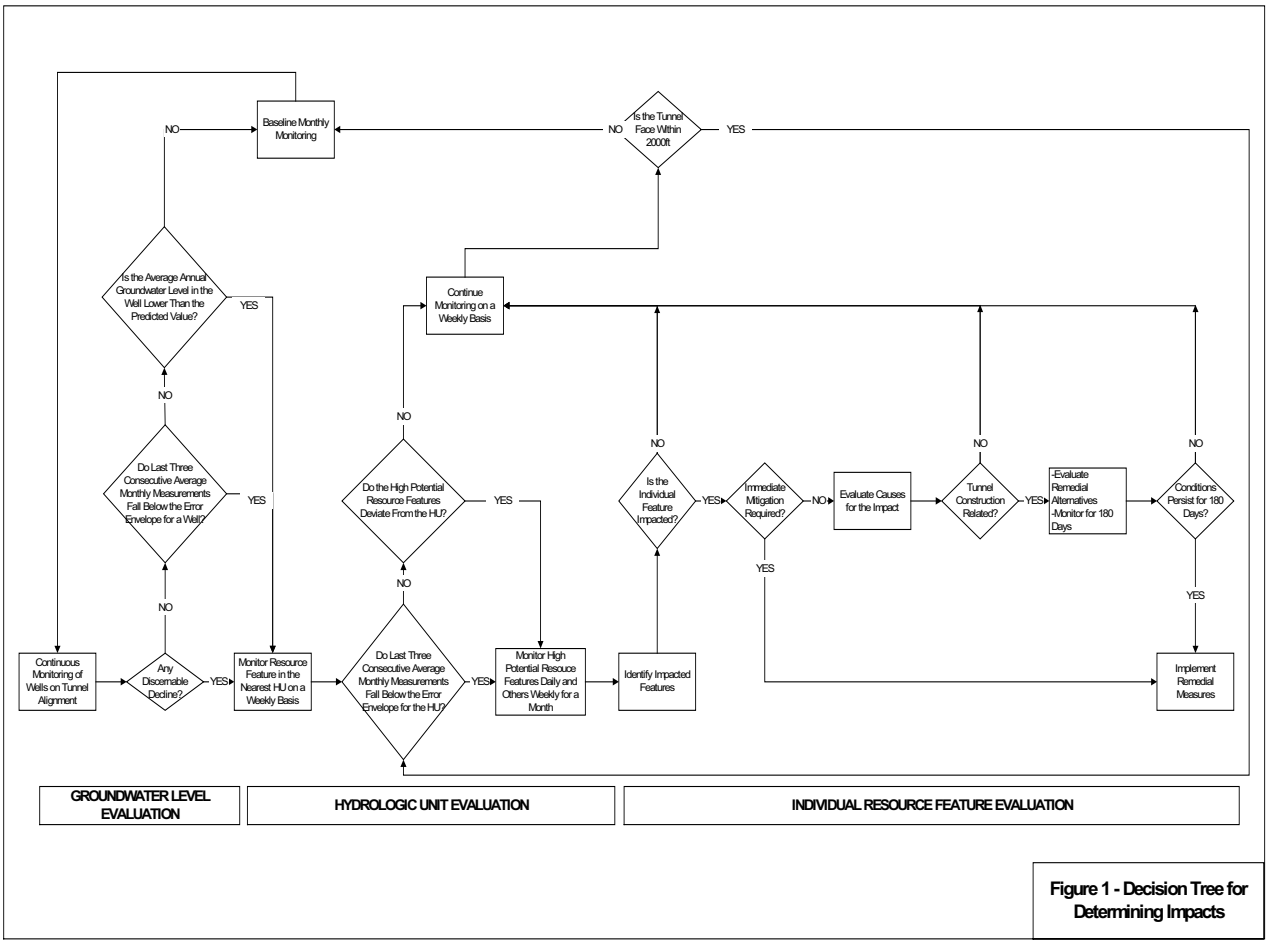
Is the Tunnel Face Within 2000ft
NO
YES
Baseline Monthly Monitoring
NO
Is the Average Annual Groundwater Level in the Well Lower Than the Predicted Value?
YES
NO
Do Last Three Consecutive Average Monthly Measurements Fall Below the Error Envelope for a Well?
YES
NO
Continuous Monitoring of Wells on Tunnel Alignment
Any Discernable Decline?
YES
Monitor Resource Feature in the Nearest HU on a Weekly Basis
Continue Monitoring on a Weekly Basis
NO
Do the High Potential Resource Features Deviate From the HU?
YES
NO
Do Last Three Consecutive Average Monthly Measurements Fall Below the Error Envelope for the HU?
YES
Monitor High Potential Resouce Features Daily and Others Weekly for a Month
NO
Is the Individual Feature Impacted?
YES
Immediate Mitigation Required?
NO
YES
Evaluate Causes for the Impact
NO
Tunnel Construction Related?
YES
-Evaluate Remedial Alternatives
-Monitor for 180 Days
NO
Conditions Persist for 180 Days?
YES
Identify Impacted Features
Implement Remedial Measures
GROUNDWATER LEVEL EVALUATION
HYDROLOGIC UNIT EVALUATION
INDIVIDUAL RESOURCE FEATURE EVALUATION
Figure 1 - Decision Tree for Determining Impacts

Figure 1. Decision tree for determining impacts

Hydrogeology of an over-exploited hard-rock area: a case study

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A b s t r a c t : Hydrogeological studies in the hard-rock area of Rasipuram have shown that the average depth of borewells has increased from about 50m to 175m during the last twenty years. The first producing zone is encountered only around 150m at present. Groundwater levels have declined sharply along with borewell yields, with majority of shallow fracture aquifers having dried up. Groundwater balance studies have shown that the level of groundwater utilization in the area varies from 80 to 225%. The zone of maximum groundwater utilization is seen to be centred on a zone, which is slightly away from the present-day groundwater trough indicating the future direction of enlargement of the trough. The increased rate of well failures has resulted in changing crop pattern and reduced area under agriculture. The groundwater is very hard and is also being subjected to contamination by starch processing industries, further increasing the stress on the groundwater environment.

INTRODUCTION

India is primarily an agrarian state and with the total area irrigated by groundwater accounting to as much as 40Mha. A large part of the country (nearly 70%) is underlain by massive crystalline rock formations, which are basically poor in groundwater resources. For a large number of populations however, it remains the only source of water, be it for domestic, irrigation or industrial use. The advent of high speed drilling technology suited for hard rocks has resulted in manifold increase in the number of borewells drilled in the last three decades leading to severe decline in groundwater levels as well as formation of over-exploited zones. The problem in such areas is twofold: depleted resources and declining quality.

STUDY AREA

The present study area is located around Rasipuram town in southern India (78° 09' 30'' to 78° 19'E and 11° 21' 30'' to 11° 30' 30''N). It enjoys a tropical semi-arid climate with an average rainfall of about 700mm/year. The area investigated has a relatively plain topography but is surrounded by steep hills to the north, east and to some extent in the south as well. Several mountain streams originate in the hills and bring surface runoff to the plains, but most of them terminate after a few kilometres, due to heavy infiltration or the presence of small reservoirs. The drainage is southwesterly, and a large number of irrigation tanks dot the landscape, majority of which remain dry through the best part of the year. Very little surface runoff takes place from the area, and thus it forms a 'closed basin'.

HYDROGEOLOGY

The study area is part of the south India granulitic terrain. Charnockites and granitic gneisses are the two important country rocks found in the area. Some exposures of intrusive dykes, banded iron ore formations and quartz veins are also seen in some places. The thickness of weathered mantle varies from nil to as much as 25m and is spatially highly variable. The area is structurally disturbed with evidence of shearing noticed in several places. Several lineaments have been identified in the area, majority of which show north-easterly trends.

The area has a very large number of dug wells and borewells with the density of borewells often exceeding 50 per km^2. The dug wells are generally quite deep, up to 45m. A large number of these dug wells are at present used only as storage tanks, to collect the discharge from borewells, for it to be later used for irrigation. This is because of the very poor discharges from borewells, which can not be directly let out to the fields. Over 1100 borewells were inventoried in the area, which, however is only a part of those present. The actual number is likely to be three to four times as many.

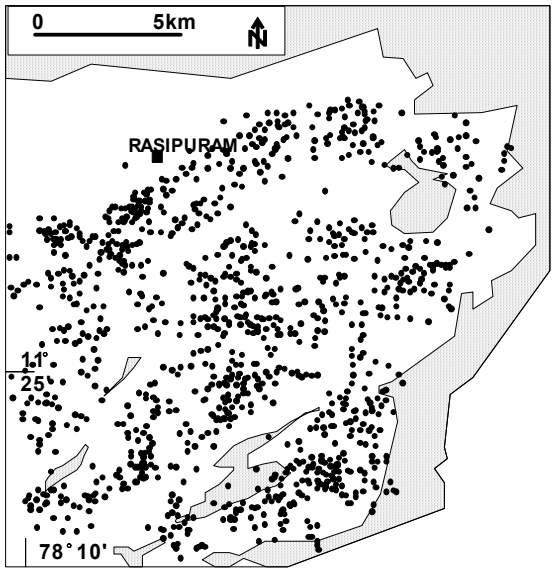

Figure 1. Map of study area. Closed circles indicate borewells; shaded portions are hills

The depth of borewells varies from 55m to 305m. The average depth of borewells drilled in any calendar year have been worked out and it is seen that there is a steady increase (Fig.2).

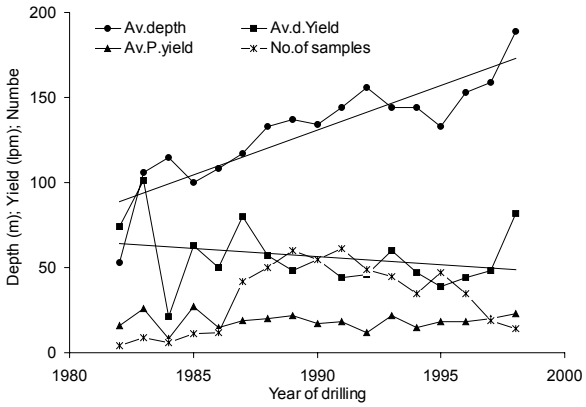

Figure 2. Trend in the Average depth of borewell. (Av.: average; P: present; d: at the time of drilling)

Even though there is a steady increase in the depth of borewells, the yields of these borewells is not directly related to their depth as seen from table 1, which gives the correlation coefficients between the depth of borewells drilled (only agricultural) in a calendar year and their yields. Such a lack of correlation is primarily due to the fact that the deeper wells are drilled consequent to the drying up of shallower fractures. It is also true that the yielding fractures may be encountered at varying depths in different borewells or that there could be very low-yielding wells even when they are quite deep. Encountering a saturated fracture at depths of more than 100m is more often a matter of chance than a certainty.

Table 1. Correlation of borewell depth and yield

year	Sample size	Ave. depth (m)	Ave. yield (lpm)	Corr. Coef. (r)
1982	4	53	74	0.32
1983	9	106	101	-0.11
1984	6	115	21	0.57
1985	11	100	63	0.37
1986	12	108	50	-0.05
1987	42	117	80	0.16
1988	50	133	57	0.27
1989	60	137	48	0.03
1990	55	134	55	0.03
1991	61	144	44	-0.06
1992	49	156	46	0.19
1993	45	144	60	0.04
1994	35	144	47	0.27
1995	47	133	39	0.01
1996	35	153	44	0.14
1997	19	159	48	0.05
1998	14	189	82	0.13

GROUNDWATER OVER-EXPLOITATION

The large-scale abstraction of groundwater has resulted in a situation where it is mined at present. A detailed groundwater balance study carried out has shown that the level of groundwater utilization (ratio of gross abstraction to available annual replenishment) is about 133% for the entire area with some zones recording as much as 225% (Fig.3)

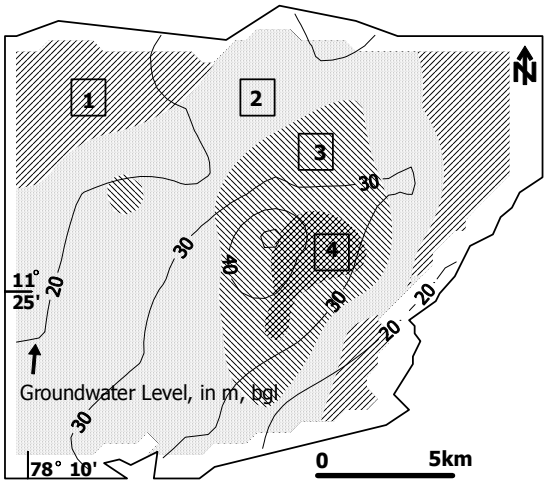

Figure 3. Map showing level of (%) groundwater exploitation in the area: 1. <100; 2.100-150; 3.150-200; 4. >200%

CONCLUSIONS

The study shows that the area is highly over-exploited and that the present level of groundwater abstraction is not sustainable. The steady decline in yields of existing borewells and the need to drill ever-deeper wells year after year indicates that the water-bearing horizons at relatively deeper levels do not get replenished by recharge and thus become unproductive after a certain period of operation. It is clear that a stage will soon come when the threshold on depth will be reached due to technical and/or financial constraints and that will have far-reaching socioeconomic implications, not only in this area but in all similarly over-exploited zones. The quality of groundwater is also declining and it is observed that in some pockets traditional crops such as paddy cannot be grown any more due to high TDS and hardness in water. Over-exploitation of groundwater in the area has resulted in:

1) reduced area under irrigated agriculture;
2) changing cropping pattern;
3) setting up of starch processing industries leading to groundwater contamination and
4) increasing TDS in water due to virtual recycling.

Northern section of the Brenner Base Tunnel: hydrogeological remarks

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A b s t r a c t : The main metamorphic units which will be crossed by the Brenner Base Tunnel in its northern section are described and hydrogeologically characterised. With regards to the risk assessment of the tunnel as a construction and the groundwater resources (springs) the study area is divided into different hydrogeological units. Methods used to determine the depth of groundwater circulation are presented. Further, the hydrochemical and physical characteristics of the hydrogeological units are shown.

INTRODUCTION

The app. 56km long Brenner Base Railway Tunnel (BBT) is planned to cross the Central Alps, an app. E–W trending mountain chain, connecting Innsbruck, Austria at 550msl with Franzensfeste/Fortezza, Italy at 750msl. With the construction of this tunnel, the railway connection between Munich, Germany and Verona, Italy, over the Brenner Pass, will be optimised. Further, the truck traffic on the motorway (A22) should be reduced due to the cargo being freighted by railway. The tunnel is planned to be finished in the next decade.

As part of a 2nd feasibility study a hydrogeological characterisation of the project area (fig.1) including a risk assessment for the groundwater resources and the tunnel construction was carried out. Two years ago a monitoring programme, which includes app. 320 measuring points at springs, rivers and cored exploration wells, was commenced and continues today. Due to the importance of the springs, which are used for water supply in 16 counties containing numerous villages and cities, and due to the fact that groundwater plays a major role in the feasibility and the costs of deep lying tunnels, a high priority is given to the factor hydrogeology.

GEOLOGICAL OVERVIEW

The northern section of the BBT will cross the Central Alps to the east of the Brenner Fault (fig.1). Thereby the Innsbruck Quartz-Phyllite Zone (Austroalpine) and the Tauern Window (Penninicum and Central Gneiss) will be penetrated. Because of its E-W extension from Austria to Switzerland and that the main transalpine traffic routes trend N-S the Tauern Window especially has been of major interest for tunnelling projects (Loew 2001).

The Central Alps are the product of complex polyphase tectonic and metamorphic regimes (Frisch 1980, Lammerer 1988). Due to the collision of the African and Eurasian Continents, during the Cretaceous and Tertiary, the former E-W trending Penninic Ocean was subducted causing north vergent thrusting with the development of stacks of nappes, metamorphism and ductile deformation. As part of the stress caused by the "Southalpine Indenter" (Ratschbacher *et al.* 1991) the overthickened crust to the north has undergone uplifting, folding and brittle deformation. With the uplifting, E–W extensional deformation started (Selverstone 1988), forming west-dipping normal faults (Brenner Fault), N-S trending extensional structures which are visible close to the Brenner Fault, and NE–SW trending brittle strike and slip faults. Due to this extension the Tauern Window, which contains the deepest tectonic units (Central Gneiss) at its centre, was formed.

As shown in the simplified geologic map of the project area (fig.1) the BBT will cross, in its northern section, the Innsbruck Quartz-Phyllite (IQP) and the Tauern Window. The Tauern Window has an onion-like structure consisting of nappes (GN, MN, HZ in fig.1) overlying the Central Gneiss (CG) in its core.

The IQP is made up of phyllites and schists, overlain by gneiss (PK in fig.1) and to the east of Matrei by the Nappes of the Tarntal Zone (TZ), a heterogeneous series of meta-sedimentary rocks of Permian-Mesozoic age. The main tectonic elements trend NE-SW.

A large north dipping thrust fault zone divides the IQP from the top nappe of the Tauern Window, the Glockner Nappe (GN). This nappe consists mainly of carbonate-rich and carbonate-poor Jurassic aged schists (Bündner Schiefer) with exotic blocks (serpentinite, rauhwacke, dolomite) in its northern most part, the Nordrahmen Zone (NZ). Some folded intra-thrust faults, containing sulphate-rich rocks, subdivide the GN. To the north of the Central Gneiss (CG) the GN dips mainly to the north and west. At the base of the GN are Permian-Mesozoic siliciclastic, carbonatic and sulphatic-rich meta-sedimentary rocks. These rocks only outcrop occasionally in the study area. The deepest unit of the Tauern Window is the Central Gneiss (CG), made up of meta-magmatic rocks, which are isoclinally folded. The CG is covered and delimited by Permian-Triassic rocks of the Hochstegen Zone (HZ) which is made up of terrigenous meta-sediments and the Hochstegen Marble.

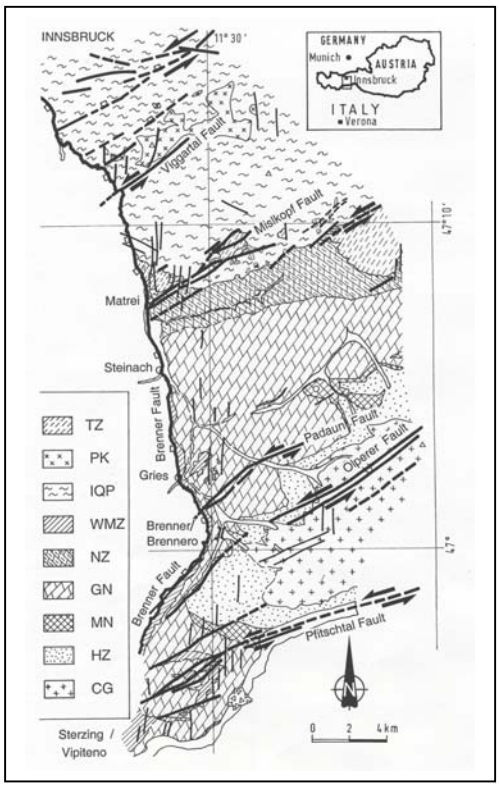

Figure 1. Simplified geologic map of the project area showing the main faults and main tectonic units (N to S): Innsbruck Quartz-Phyllite (IQP); Patscherkofel Crystalline (PK); Nappes of the Tarntal Zone (TZ); "Nordrahmen Zone" (NZ); Glockner Nappe (GN); Modereck Nappe (MN); Central Gneiss (CG); Hochstegen Zone (HZ); Wipptal Melange Zone (WMZ)

Probabilistic delineation of groundwater protection zones in fractured-rock aquifers

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A b s t r a c t : Groundwater protection zones in fractured rock aquifers were delineated using a hybrid approach which combines the use of discrete fracture network (DFN) models and equivalent continuum models. The method used, known as the Statistical Continuum Method (SCM), relies on statistics of movement of particles in a local-scale DFN followed by the use of those statistics to mimic movement in a catchment-scale continuum model. Because the method is based in a Monte-Carlo procedure, it is possible to delineate probability contours for protection zones. The method was implemented in a catchment-scale synthetic case study, using MODFLOW as the continuum groundwater flow model. Reverse particle tracking was conducted and the locations of the particles at time *t* were used to create probability contours of the *t*-isochrone protection zone. The computational requirements for upscaling from local scale to regional scale are not heavy and probability contours of protection zones can be easily computed.

INTRODUCTION

The delineation of Groundwater Protection Zones in fractured rock aquifers generally involves the assumption that the aquifer can be treated as an Equivalent Porous Medium. Although several studies have proved that such an assumption is often not met, the difficulty in dealing with the discontinuity and heterogeneity of those rocks leaves few alternatives. Discrete Fracture Network (DFN) models can be used for local scale studies, but other alternatives must be sought for upscaling to catchment-scale.

The Statistical Continuum Method (SCM) is a suitable tool for upscaling from local to regional scale. This study is concerned with the use of that method to delineate probabilistic contours of Protection Zones.

Background on the Statistical Continuum Method

The Statistical Continuum Method attempts to merge the accuracy of discrete models when representing the physics of flow and transport with continuum models which have fewer limitations on domain size but which do not accurately represent the physics of the transport process.

The method was first enunciated by Schwartz and Smith (1988) and refined by Smith *et al*. (1990), Parney and Smith (1995) and Parney (1999). It consists in using particle tracking in which physical transport is simulated in terms of velocity and velocity variations. Statistics describing the particle motion come from observing the actual pattern of particle motion in a discrete sub-domain. This subdomain should be a small but representative piece of a much larger continuum. Particle motion in the continuum is then forced to mimic that in the discrete subdomain.

The statistics collected are the frequency that a particle chooses to move in each direction and frequency distributions of fracture lengths between intersections (pathlength), speed and standard deviation of speed in each direction.

The major strengths of the SCM are (Long 1996) that it allows upscaling at a regional scale without the need to account for every fracture; makes no assumption about Fickian behaviour; and particle tracking is conducted in the DFN domain and then the continuum model mimics movement without considering dispersion tensors.

Implementation and Application to Catchment-scale domain

In order to implement the SCM so that it can be used for delineation of Protection Zones it is necessary that the method can deal with complex flow situations, involving the common types of boundary conditions and wells. Implementation should be carried out as follows:

- collect the statistics (indicated above) for several orientations of the hydraulic gradient, so that a matrix can be created with those distributions as variables for each hydraulic gradient orientation. This is accomplished using a DFN code in which particle tracking is conducted for several orientations of the hydraulic gradient;
- the statistics must consider every possible direction of movement along the existing fracture sets, both according and opposite to the overall hydraulic gradient orientation;
- link SCM to a standard groundwater modelling program, such that it can recognise the groundwater flow solution and conduct the particle tracking according to the statistics collected in the DFN domain. At each location the hydraulic gradient is computed and the distributions of direction and pathlength are used to generate each particle movement. The distributions of velocity are used to compute the travel time for each movement. This procedure is repeated until the total travel time is reached;
- create probability contours that a given cell is part of the Protection Zone. This procedure is described further below.

A code was written to implement this procedure. An important issue was to decide if SCM should be applied in 2D or 3D modelling. We will be dealing only with well-connected networks, so 2D is a reasonable approximation.

To test the use of the SCM a synthetic case study was created based on a PMWIN example (Chiang and Kinzelbach 2001). A confined fractured aquifer has north and south impermeable irregular boundaries, while the east and west boundaries are constant head. Three wells pumping at constant rate create a complex flow pattern. The aquifer was discretized into cells larger than the size of the discrete fracture network from which the SCM would provide the statistics. Also, the fracture characteristics of the aquifer were considered as homogeneous throughout the whole domain, according to tab.1 and fig.1. Should fracture characteristics vary across the aquifer, different statistics of movement should be collected and applied in the relevant cells.

Table 1. Fracture statistics

Fracture orientation	Fracture density (m^{-1})	Fracture length		Aperture (m)
		Mean (m)	Variance (m^2)	
N110º, 15ºNE	0.6	4.0	2.2	5×10^{-5}
N145º, 65ºE	0.6	2.7	2.2	5×10^{-5}
N20º, 55ºW	1.2	3.3	2.2	1×10^{-4}

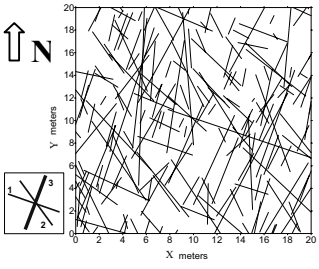

Figure 1. Sample realization of the fracture network for a 20m×20m area. In the small square, thickness of the fractures is proportional to aperture. Density and aperture of set 3 cause a high anisotropy of the network. Code SDF (Rouleau, Gale 1987) was used to generate the DFN

A DFN domain was used to collect the statistics for several orientations of hydraulic gradient. The DFN domain had a rectangular area of 75m×75m, with constant head boundaries at X=0m and X=75m, and impermeable boundaries at Y=0m and Y=75m.

To assess the SCM reliability with respect to the 'exact' DFN solution, the statistics were used to model solute transport in a continuum domain with the same boundary conditions. The DFN and SCM results were compared by plotting the 1st (mean) and 2nd (variance) moments about the mean of the particles location (fig.2).

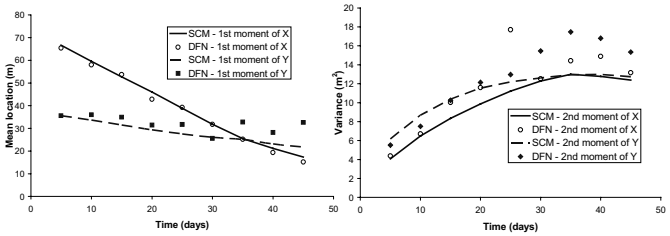
SCM - 1st moment of X
DFN - 1st moment of X
SCM - 1st moment of Y
DFN - 1st moment of Y
Mean location (m)
Time (days)
SCM - 2nd moment of X
DFN - 2nd moment of X
SCM - 2nd moment of Y
DFN - 2nd moment of Y
Variance (m²)
Time (days)

Figure 2. Location moments of X and Y. Particles were released at X=75m, Y=37.5m

For travel times up to about 30 days the approximation between SCM and DFN solutions seems to be acceptable. After 30 days the dispersion in the y direction in the DFN domain is much larger than for the SCM. This is due to the fact that, after 30 days, particles start reaching the boundaries and SCM no longer uses them to compute the moments. Dispersion in the DFN domain is always a bit larger because in the DFN domain particles must be shifted to the closest node of the fracture network. Since the DFN involves multiple realisations, particles do not start exactly at the same location resulting in an 'artificial' increased dispersion.

The next step is to solve the groundwater flow problem to get values of hydraulic gradient at each point of the continuum domain, since that is the only parameter used by SCM to mimic particle tracking. The program MODFLOW (via the interface PMWIN) was used to solve for the head, then the SCM computes the hydraulic gradient at each location of every cell.

To find the flow solution, the hydraulic conductivity (K) and effective porosity (n_e) parameters must be consistent with the characteristics of the fracture system. Pumping tests and tracer tests were simulated in the DFN domain. The values found: $K_x=10^{-3}$ m/d, $K_y=5.8\times10^{-3}$ m/d and $(n_e)_x=6\times10^{-5}$, $(n_e)_y=9\times10^{-5}$.

The results of the SCM were compared with the capture zones delineated using an Equivalent Porous Medium (EPM) model that allows anisotropy both in K and n_e. In the SCM dispersion is important and the main flow directions are imposed by the most permeable fracture set, oriented at N20º. The results of the SCM seem to be consistent with the imposed flow field and with the anisotropy of the fracture system (fig.3).

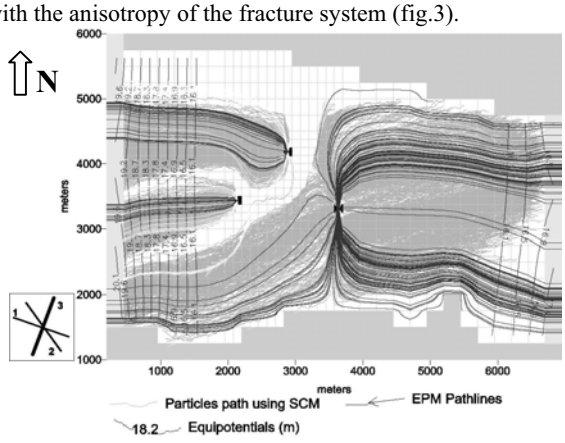

Figure 3. Capture zones of 3 wells in an aquifer with an 'anisotropic' fracture network. In SCM tracking was limited to 10000 days, thus some of the paths do not reach the limit of the capture zone

Uncertainty Contours of Groundwater Protection Zones

Using the location of the several particles through time, it is possible to delineate protection zones for any isochrone. Since the movement of the particles is based on distributions of pathlength and velocity, the arrival time is also described according to a distribution. Therefore, contouring must be probabilistic.

To quantify uncertainty, for each cell the number of particles that reach the well after time *t* is divided by the total number of particles that reach the well. The final result is the probability that each particle travelling through that cell will take longer than time *t* to reach the well. Thus the 75% contour means that 75% of the particles take longer than *t* to reach the well.

There is considerable difference between the protection zones delineated with an Equivalent Porous Medium approach and those delineated with the SCM (fig.4), both in orientation and in size of the protection zones. SCM delineates larger protection zones due to the channelling effect that causes particles to flow primarily along more conductive fractures are due to the dispersion effect.

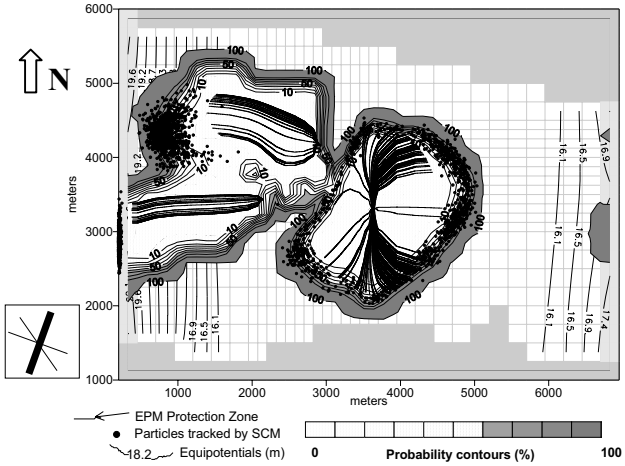

Figure 4. Ten-year protection zones

CONCLUSIONS

The Statistical Continuum Method seems to provide a useful way for simulating mass transport in fractured rocks at scales greater than the ones that can be simulated by discrete fracture network models. SCM is easy to implement and to use in conjunction with standard finite difference groundwater flow codes to compute probability contours of protection zones at the catchment scale.

REFERENCES

Chiang W-H, Kinzelbach W (2001) 3D-groundwater modeling with PMWIN : a simulation system for modeling groundwater flow and pollution. Springer, Berlin; New York, xiv, 346 pp

Long J (ed) (1996) Rock fractures and fluid flow: contemporary understanding and applications. National Academy Press, Washington DC, 551 pp

Parney R, Smith L (1995) Fluid velocity and path length in fractured media. Geoph Res Letters 22(11):1437-1440

Parney RW (1999) Statistical continuum modeling of mass transport through fractured media, in two and three dimensions. Unpublished PhD thesis, Univ. of British Columbia, 325 pp

Rouleau A, Gale JE (1987) Stochastic discrete fracture simulation of groundwater flow into an underground excavation in granite. Intl J Rock Mech Min Sci & Geomech Abstr 24(2):99-112

Schwartz FW, Smith L (1988) A continuum approach for modelling mass transport in fractured media. Wat Res Res 24, 8:1360 - 1372

Smith L, Clemo T, Robertson M (1990) New approaches to the simulation of the field-scale solute transport in fractured rocks. In: Bachu S (ed) Proc.5th Canadian/American Conference on Hidrogeology,Dublin (Ohio), 329-342

Breeding impacts on groundwater pollution in carbonate aquifers

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A b s t r a c t : Drinking water in carbonate aquifers are often contaminated by cattle grazing and manure spreading. The microbial pollution is characterised by high spatial and temporal variability, as a function of the interaction between several factors. The research was carried out in a carbonate aquifer of Southern Italy to define (a) the influence of several factors on both the entity and the temporal variability of contamination and (b) the reliability of fecal streptococci as indicators of groundwater bacterial contamination. The microbial contamination of springs' water showed a cyclic behaviour, strictly related to precipitations. It appeared when (a) surface water significantly and fastly interacted with groundwater and when (b) large quantities of dung were concentrated in areas close to the springs. The statistical analysis of the data showed that fecal streptococci are better indicators than fecal coliforms when the mean values of microbial contamination of groundwater are low.

INTRODUCTION

The carbonate aquifers provide the main drinking-water resources of Southern Italy, supplying an average volume of $4100*10^6$ m3/y (Celico 1983; Celico *et al*. 2000). Because of the existence of karst systems, fast interactions between surface and groundwater are often produced. Therefore, significant quantities of contaminants can be rapidly transported into the subsurface (Celico *et al.* 2002).

Because of the high slope gradient (often higher than 40%), the only human activity generally allowed is the cattle grazing. Manure is spread in karst planes.

The purpose of the present study was to define (a) the influence of precipitations, infiltration modalities, transport pathways and dilution on both the entity and the temporal variability of contamination and (b) the reliability of fecal streptococci as indicators of groundwater bacterial contamination. The study was developed through the monitoring of microbial contamination of 4 springs, from January 2001 to March 2003, in the study site of "Acqua dei faggi" carbonate aquifer (Southern Italy).

STUDY AREA

Acqua dei faggi carbonate massif is a fractured aquifer, with rare karst conduits, about 16 km^2 large. It is constituted by calcareous deposits (Cretaceous-Oligocene) and, subordinately, by marly-calcareous (Oligocene-Burdigalian) and calcareous-marly deposits (Langhian-Tortonian). The boundaries of the aquifer are represented by the tectonic discontinuities which produced a significant decrease of the hydraulic conductivity of the carbonate rocks.

The mean annual infiltration is about 650 mm/y. The recharge is represented by both the direct and diffuse infiltration of the rainfall and the secondary infiltration of surface water in a closed basin and along a stream.

The groundwater flows from East toward West, to different springs, identified as springs "A", "B", "C" and "D".

The intermittent spring "A" (1065 meters a.s.l.) is fed by the secondary and concentrated infiltration of runoff in a swallow hole located 350 meters from the spring. The spring and the swallow-hole are directly interconnected through an explored karst conduit. Therefore, the monitoring of this spring has allowed the analysis of the interaction between microbial pollutants and the karst conduit, in a pasture area. Only intense rainfall events are able to produce this secondary infiltration.

The seasonal spring "B" (1035 meters a.s.l.) has a mean annual discharge of about 0,01 m^3/s and is fed by both the direct and the secondary infiltration water. The surface water, before flowing within a karst conduit (which is entirely located in the non saturated medium), infiltrates in a depression through the soil medium, 400 meters from the spring. This conduit represents a portion of the karst system interconnected with the spring "A". Both the direct and the secondary infiltration water interacted with pasture.

The perennial spring "C" (985 meters a.s.l.) has a mean annual discharge of about 0,08 m^3/s and is not interconnected with karst conduits. Manure was spread in a small plane located 200 meters from the spring.

The perennial spring "D" (685 meters a.s.l.) has a mean annual discharge of about 0,11 m^3/s and is fed by both the direct and the secondary infiltration water. The surface water interacted with pasture and linearly infiltrated (a few litres per second) along a fractured stream bed located more than 500 meters from the spring. Since June 2001 a new stock farm was realized near the spring (less than few tens meters).

The depletion constant of the seasonal and the perennial springs go from $3,3 \times 10^{-3}$ and $3,5 \times 10^{-2}$ d^{-1}. The groundwater level was characterised by a fast evolution produced by the effective infiltration, showing high flow velocities within the non saturated fractured medium (24 ÷ 27 m/d).

The sources of contamination are represented by seasonal pasture (allowed from May to October and developed in the 34,7% of study area) and manure spreading (developed in the 9,6% of study area). The 55,7% of the aquifer is covered by beech woodland. In pasture areas the carbonate slopes are covered by Epilepti-Vitric Andosols (Mollic), whereas the manure is spread in the karst planes where Pachi-Vitric Andosols (FAO 1988) outcrops.

RESULTS

Surface water which infiltrated into the aquifer (secondary infiltration) always showed from several tens to several hundreds CFU/100 ml of fecal bacteria.

A significant microbial pollution was verified in the water samples collected in spring "A" (from several tens to several hundreds CFU/100 ml of fecal bacteria), during the rainfall event which produced a secondary infiltration of surface water in the swallow hole directly interconnected with the spring.

No microbial pollution was verified in the water samples collected in spring "B" during rainfall events which did not produce significant runoff (and secondary infiltration). Yet, a low microbial pollution (few CFU/100 ml of fecal bacteria) was verified in the water samples collected in spring "B" during the rainfall events which produced significant runoff and the surface water infiltration through the soil medium superimposed on karst conduit. A greater microbial pollution (several tens of CFU/100 mL of fecal bacteria) of water samples collected in spring "B" was verified when intense rainfall events produced the

concentrated infiltration of the runoff in the swallow hole indirectly interconnected with the spring. That showed a significant interaction between karst system and fracture pattern. In any case, it was verified a cyclic evolution of the microbial contamination, strictly related to precipitations.

It was also verified a cyclic microbial pollution (from few to several few hundreds CFU/100 mL of fecal bacteria) in the water samples collected in spring "C" during significant direct infiltration events.

No microbial pollution was verified in the water samples collected in spring "D" before June 2001, although the surface water of the stream linearly infiltrated into the aquifer (few L/s). From June 2001 on the new stock farm nearby the spring produced a significant increase of the microbial pollution of spring water.

The statistical analysis of the data have also shown the absence of fecal coliforms in many contaminated water samples (fecal streptococci ≥1).

DISCUSSION AND CONCLUSIONS

The influence of pasture and manure spreading on the groundwater microbiological contamination in carbonate (fractured – karstified) aquifers significantly changes as a function of the infiltration modalities (direct or secondary), the transport pathways (fracture pattern or karst conduits) and the dilution degree. As a matter of fact, the interaction between microbial contamination and karst conduits did not allow a significant self-purification of polluted water. Low contamination of spring water was verified when the infiltrated surface water was about 1/10 of the groundwater discharge, although their interaction with the soil medium superimposed on karst conduits (spring "B"). On the contrary, no contamination of spring water was verified when the infiltrated surface water was about 1/100 of the groundwater discharge (spring "D").

The direct infiltration of polluted water, through soil and limestones, produced significant microbial contamination only when there was a stock farm nearby the spring ("D") and when there was manure spreading at a medium distance from the spring ("C"). In other words, the direct infiltration was able to generate the microbial contamination of a spring just in case large quantities of dung were concentrated in a small area close to the spring (short lengths of transport). As a matter of fact, the soil media were never able to produce a complete self-purification of polluted water. That was confirmed by the results of column tests.

In all cases of contamination, the microbial pollution was characterised by a cyclic evolution, strictly related to precipitations, thanks to the high flow velocities and / or the medium-short lengths of transport.

Concerning the reliability of the microorganisms analysed, the statistical analysis of the data showed that fecal streptococci are better indicators than fecal coliforms when the mean values of microbial contamination of groundwater are low (in the case study, few CFU/100 ml). That should be interpreted as the result of different factors: (a) animal feces are characterised by a ratio fecal coliforms / fecal streptococci below 0,7 (Geldreich and Kenner 1969), (b) fecal streptococci are more resistant than fecal coliforms in the environment (Gleeson and Gray 1997), (c) the filtration of fecal coliforms through the soil media of study area could be more efficient than that of fecal streptococci.

As a matter of fact, in many cases the detection of microbial contamination of groundwater and the analysis of its evolution must be developed through an intensification of the "classic" groundwater quality monitoring and through the utilization of fecal streptococci together with fecal coliforms.

REFERENCES

Celico F, Celico P, De Vita P, Piscopo V (2000) Groundwater Flow and Protection in the Southern Apennines (Italy). Hydrogeology 4:39-47

Celico F, Musilli I, Naclerio G (2002) The Impact of Pasture and Manure Spreading on Microbial Groundwater Quality in Carbonate Aquifers. In: Bocanegra E, Martinez D, Massone H (eds) Groundwater and Human Development – Proc. XXXII IAH & VI ALHSUD Congress, Mar del Plata (Argentina), October 21-25, 205-209

Celico P (1983) Le Risorse Idriche Sotterranee dell'Appennino Carbonatico Centro-Meridionale. Idrotecnica 1:3-18

FAO (1988) Soil Map of the World. Revised Legend. World Soil Resources Report 60. FAO, Rome

Geldreich EE, Kenner BA (1969) Comments on Fecal Streptococci in Stream Pollution. J Water Poll Control Fed 41:336-341

Gleeson C, Gray N (1997) The Coliform Index and Waterborne Disease E and FN Spon, London

Using adapted testing tools and testing program to estimate water drainage from tunnels under construction and tunnels in service

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A b s t r a c t : A new approach has been developed for hydrogeological testing of deep exploratory boreholes using packer systems that are pumped through the drill string. Water is produced from the isolated interval during the test sequence. Transient pressure reactions measured in the isolated interval are analysed using semi-log and the log-log approach where pressure and pressure derivatives are plotted versus time. The interpretation software used allows applying various aquifer models as well as the analysis of horizontal wells. The drainage into a future tunnel is calculated with the same software considering the tunnel as a large horizontal borehole with water inflow under atmospheric pressure.

INTRODUCTION

The water drainage into a tunnel is the quantity of water seeping naturally from the formation as a result of pressure difference (formation pressure - atmospheric pressure) existing in this tunnel. Initial drainage, for tunnels under construction, is always more important than stabilised drainage for tunnels in service. In general, one considers that the formation is hydrogeologically "active" when the stabilised drainage exceeds 50 litres per second (3 m^3 per minute).

For decades, the determination of water drainage has been qualitatively estimated from geological considerations or from the normalised approach using Lugeon type injection tests in vertical wells crossing the path of the future tunnel. It is now recognised that this approach is not quite appropriate. A new approach has been developed which is based on the use of sophisticated testing tools, in particular in horizontal well sections drilled along the path of a future tunnel. These horizontal sections can be drilled before tunnel construction from the surface with exploratory wells using the directional drilling method, or they can be drilled from the excavation face in a tunnel under construction.

TESTING TOOLS

Various types of testing tool have been used for hydrogeological testing during the last decade, such as combined logging and testing systems applied along the entire open-hole section, double packer systems run with drill pipes or special tubing, and wire-line packer systems run through the coring assembly (Bühler and Thut 1999). They all include a surface pressure read-out system for data transmission (Delouvrier *et al.* 1999)). Now a new concept, a "Pump-Down Packer System" (PDPS) combined with a "Shut-Off Packer" (SOP) has been developed by the authors for horizontal wells drilled from the surface. This tool has been used for hydrogeological testing for a base drainage calculation along a deep tunnel project in the French Alps (project Alpetunnel-LTF), along the path of a future railway tunnel between Lyon and Turin (Bois and Bertrand 2001).

The tool is presented fig.1. After coring a new section, the coring string is partially retrieved from the end of the borehole (say about 50/100 m). The PDPS is then pumped through the drill string and the tool lands on a no-go-shoulder at the coring bit. In such a configuration, a first "external" packer passes through the coring bit into the open-hole, and a second "internal" packer remains inside the coring string. Increasing the pump pressure at the surface causes the two packers to inflate and opens a passage between the interval below the external packer and the drill string above the internal packer. Testing operations can then be performed on the isolated section between the external packer and the end of the borehole. Pressure and temperature are continuously monitored in the tool by means of two downhole recorders. An integrated downhole sampler enables one to take a water sample at the end of the testing operation.

A second packer system (SOP) is installed inside the drill rods to a depth of a few hundreds meters (depending on the water level). This system is run and set with small diameter tubing inside the coring string in the vertical or inclined part of the well. A downhole shut-in valve allows one to create production and shut-in periods. A surface pressure read-out system is used to transmit dowhole pressure to the surface. The system allows swabbing, airlift or pumping operations in order to produce water from the test interval during the testing sequence.

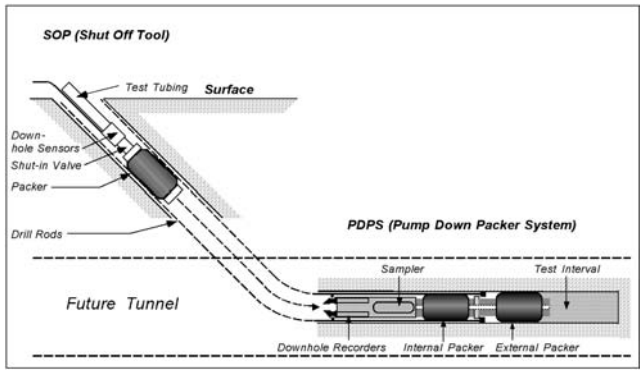

Figure 1. Pumped packer system used in deep directionally-drilled wells

Once the test is finished, the SOP is retrieved, and the coring string is pulled, which initiates deflation of the two PDPS packers. The last operation is to run the wire-line overshot used to retrieve the core barrel during the normal drilling operation. Now the overshot is used as a fishing tool to retrieve the PDPS. Once the PDPS has been retrieved, the coring operations can resume.

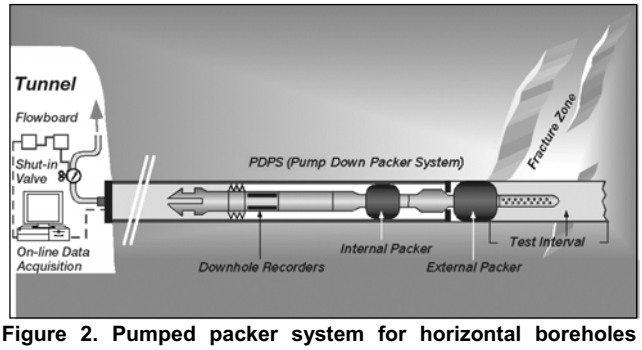

Figure 2. Pumped packer system for horizontal boreholes drilled ahead of the excavation face

The same PDPS concept has been also used in horizontal wells drilled ahead of the tunnel excavation face in the Lötschberg base tunnel project (fig.2). Expected water pressure of up to 70 bar required drilling with a preventer system for security reasons and did not allow using a double packer system installed with tubing and with cables. In boreholes drilled from the tunnel, water flows naturally from the formation to the tunnel. For this reason, the wellhead valve at the end of the drill string in the tunnel replaces the SOP shut-in valve of the above concept, and samples are directly collected at this point.

TESTING PROGRAM AND INTERPRETATION

The testing program for the tool object of fig.1 is mainly based on DST (drill stem test) sequences, a combined slug and pulse test approach. This approach originates from the petroleum industry, where it has been used for decades. The testing program for the tool object of fig.2 is based on a succession of natural flow and shut-in sequences. In both cases, the surface pressure read-out system allows a real-time data transmission and interpretation, so that the test program can be permanently adapted to the well behaviour. However, test interpretation is performed on downhole data transferred from the pressure-/temperature-recorders after retrieval of the tool.

The interpretation methodology is based on a pressure and pressure derivative analysis versus time on a log-log plot. This approach was developed in the 1980s for the petroleum industry and is now becoming a standard in hydrogeology. Once an initial interpretation has been performed, simulation and non-linear regression techniques are used to improve the analysis. If necessary, various aquifer models can be applied, and the process is repeated until a good match is obtained between the experimental points and the simulation.

Fig.3 is an example of such a log-log plot. The specific "half slope" shape of the pressure and pressure derivative curves is typical for a major flow in the tested interval along highly permeable fissures, and indicates that serious safety problems might be encountered in this zone during the tunnel excavation.

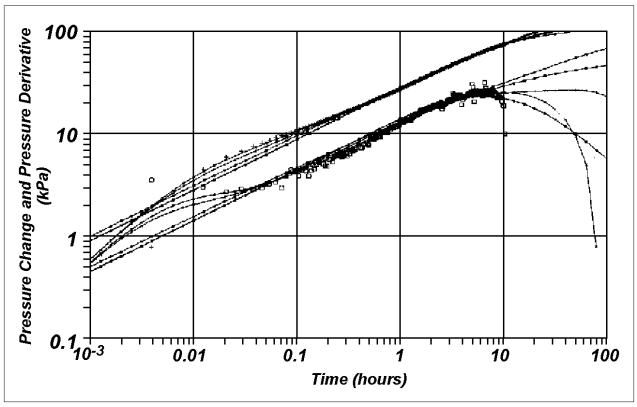

Figure 3. Log-log diagnostic plot of pressure change during hydraulic testing

DRAINAGE CALCULATION

Drainage calculations are performed with the same interpretation software used for test analysis. As a matter of fact, a tunnel behaves like a very large and long horizontal well; about 10 m in diameter instead of 10 cm, and several kilometres long instead of one or two kilometres. The hydrogeological parameters of a given interval are entered as input parameters in the horizontal well model of the software, with dimensions of the tunnel. Flow prediction (drainage) is simulated using atmospheric pressure as the flow pressure.

Fig.4 depicts an example of such a drainage calculation and shows how a bad interpretation can affect the drainage results. The initial drainage rate increases from 600 to 9000 litres per minute, and the stabilised drainage rate increases from 600 to 5000 litres per minute (curve 2 to curve 1) if the interpretation software takes into account the "clogging" effects (skin-effect) during the test sequence, and if it can retrieve this effect during the drainage simulation. This "active" interval would have been considered as "inactive" if the skin effect was not retrieved from the drainage calculation. This kind of interpretation was impossible with the Lugeon tests, and explains the lack of representativity of their drainage results.

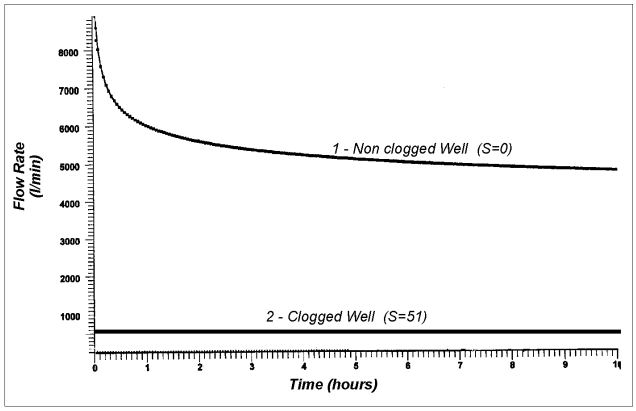

Figure 4. Tunnel drainage simulation using the "rate drainage" option of the interpretation software "Saphir"

CONCLUSIONS

A new approach is proposed for drainage calculations. It is based on the use of pumped testing tools in horizontal well sections drilled along the path of a future tunnel, and the use of interpretation techniques using pressure and pressure derivative analysis. The same interpretation package is used to calculate initial and stabilised drainage rates, using a horizontal well model in order to simulate inflow to the tunnel. The estimated stabilised drainage inflow will help in the design of the drainage pumping system of the future tunnel. In addition, it can be a tool to decide if a producing fracture zone has to be sealed (grouted) or if it can be drained in cases where the total outflow from the tunnel is limited for environmental reasons.

REFERENCES

Bois AP, Bertrand L (2001) Reconnaissances par sondages dirigés. Document Alpetunnel GEIE , January 2002

Bühler Ch, Thut A (1999) Hydraulische und felsmechanische Bohrlochversuche, Vorerkundung und Prognose der Basis-tunnels. Löw & Wyss Ed Balkema, Rotterdam. ISBN 90 5410 480 5

Delouvrier J, Thut A, Seguin M (1999) Les mesures hydro-géologiques pour la caractérisation des ouvrages souterrains profonds. Journées internationales de l'AFTES sur les travaux en souterrains, Paris, Octobre 1999

Influence of lithology on persistence of NAPL in fractured aquifers

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Abstract: Fractures provide pathways for rapid subsurface migration of contaminants, both as non-aqueous phase liquids (NAPLs) and dissolved in groundwater. The relative movement of free and dissolved phases is controlled by different features of the aquifer system, particularly fracture orientation and aperture, as well as by the contaminant source term and properties. The mobility and persistence of NAPL in fractures is influenced by the rock matrix lithology, porosity and permeability. Field observations from sites with a long industrial history show that NAPLs may persist in fractures for years or decades, especially where some components of the NAPL are of limited solubility. Field data from five sites in North America and the UK are presented, representing a range of conditions where NAPLs have penetrated to significant depths and persisted in subsurface fractures for a prolonged period. The examples include fractured clay, sandstones with variable degrees of cementation and weathering, and dolomite.

INTRODUCTION

Fractures provide pathways for rapid subsurface migration of contaminants, both as non aqueous phase liquids (NAPLs) and as a dissolved phase in the groundwater. However, site investigation and characterisation of NAPLs in fractured media can be technically difficult and expensive, but good data are essential for understanding of the fracture network and the interaction between fractures and the matrix. The relative movement of free phase and dissolved phases is controlled by different features of the aquifer system, particularly fracture orientation and aperture, as well as by the contaminant source term and properties. The persistence of both NAPL and dissolved phase in fractures is influenced by the rock matrix lithology, porosity and permeability.

Field observations from sites with a long industrial history show that NAPLs may persist in fractures for years or decades. This is particularly evident in cases where some components of the NAPL are of limited solubility, e.g. unrefined hydrocarbons, lubrication oils and coal tar. The behaviour and mobility of the NAPL and the dissolved phase are strongly influenced by matrix lithology, as well as the fracture network. Field data from five sites in North America and the UK are presented, representing a range of conditions where NAPLs have penetrated to a significant depth and persisted in subsurface fractures for a prolonged period, thus forming a continuing source of groundwater contamination.

THEORETICAL BACKGROUND

Movement of NAPLs in a fractured rock depends on the properties of the NAPL, the fracture network, the aperture and orientation of individual fractures and the groundwater regime. Relatively small volumes of NAPLs in vertical or subvertical fractures can fill a significant height of fracture, thus generating a pressure difference between the NAPL in the fracture and the water in the matrix (Kueper and McWhorter 1991). The depth of penetration of DNAPLs (denser than water) is determined by fracture aperture, NAPL density and viscosity (Pankow and Cherry 1996), but slowed by dissolution (Parker *et al*. 1997). The advance of the DNAPL may cease altogether due to a constriction with a large entry pressure, but a rise in DNAPL pressure or changes in capillary forces may allow sudden remobilisation (Ross and Lu 1999).

Despite being less dense than water, LNAPLs in fractures can penetrate into the saturated zone, depending on the connected vertical height of LNAPL, its density and the fracture aperture. In large aperture fractures where the effects of capillary forces are reduced, the depth of penetration may be several orders of magnitude greater than that predicted by porous medium models (Hardisty *et al.* 1998). This may and allow movement of LNAPL into interconnected sub-horizontal fractures, thus providing a pathway for lateral spreading.

Previous theoretical treatments (Parker *et al.* 1997) have predicted comparatively rapid disappearance of NAPLs from fractures, particularly in cases where the bulk of the NAPL is made up of relatively water-soluble components, and the rock matrix has significant porosity and permeability. The disappearance time of a single component NAPL from planar fractures due to dissolution and diffusion depends on the ratio of available mass storage in the matrix to the initial storage capacity in the fractures. Calculated times range from 0.3 to 12 years for trichloroethylene in a typical fractured clay and sandstone, respectively, with a fracture spacing of 1 m (Parker *et al.* 1997).

However, in situations involving multi-component NAPL mixtures, where some of the components are of limited solubility, NAPLs may persist in fractures for extended periods of time. Unrefined hydrocarbons, lubrication oils, PCB's and coal tar are examples of such liquids. Where the rock matrix is of low permeability, diffusion processes may be slow. In large aperture fractures with significant NAPL saturation, reduced surface area of contact between NAPL and groundwater, per unit volume of NAPL, may also contribute to enhanced persistence.

FIELD OBSERVATIONS

The industrial history of the UK has left a legacy of contaminated, urban sites, which require investigation and remediation prior to redevelopment. Many of these sites were active for over 100 years, and thus provide unique information on the long-term behaviour of both NAPLs and dissolved phase contaminants. However, due to the long history, precise definition of the source terms is rarely possible.

Systematic investigation of contamination in North America also provides good data on the long-term behaviour of contaminants, generally in the 20 to 50 year time scale.

Field data from five sites in North America and the UK are presented, representing a range of conditions where NAPLs have been found in subsurface fractures, implying persistence for years or decades. Comprehensive investigations, including several phases of drilling, sampling and monitoring, have been undertaken at all the sites. The examples include gas condensate LNAPL in a fractured Cretaceous sandstone aquifer, coal tar DNAPL in fractured and weathered Triassic sandstones, coal tar in fractured alluvial clay, and unleaded motor fuel in a fractured dolomite.

Tab.1 summarises the key information from the site investigations, including a brief description of the fracture orientation and spacing, matrix properties, contaminant type and estimated time since contamination first occurred. The table aslo includes the maximum depth of penetration of NAPL as observed during the site investigation.

DISCUSSION

Three of the sites are former gasworks where the principal contaminants are by coal tars and their derivatives, with a density which is similar or slightly greater than water. The results from the first example show that the widely spaced, vertical fractures allow NAPL to penetrate to a significant depth, even though the tar is highly viscous and the rock is a thick plastic clay of low permeability.

The other two gasworks sites lie on the outcrop of one of the UK's major aquifers, the Triassic Sherwood sandstone, close to the feather edge of the aquifer. The stratigraphic position, lithology and thickness of the sandstone, and nature of the superficial cover are very similar at both locations. However, there are some striking differences in the depth of penetration and the distribution of the free phase tars. These are interpreted as being due to minor changes in lithology and the degree of weathering, which result in subtle variations in grain size, cementation and fracturing. More intense weathering results in a friable aquifer with fractures infilled by sand. Where the sandstone is more competent, occasional vertical fractures play a major role in allowing downward movement of NAPL and providing access to interconnecting, sub-horizontal fractures. NAPL can only enter the sandstone matrix of a few, coarse grained beds with larger pore throats, while occasional unfractured, fine grained beds prevent further downward movement. However at both sites, comparison of hydraulic conductivities from cores and pumping tests suggest that the fractures make only a small contribution to bulk transmissivity.

The contrasting results for the two remaining sites, both in North America, illustrate the influence of the duration of the source and the fracture network. The relatively short time since the spill into the dolomite, combined with a rapid decrease in fracture density and aperture with depth, results in a limited penetration of NAPL into the deeper aquifer. However, due to pumping, the movement of dissolved phase is not limited in the same way. At both these sites, diffusion into the matrix is extremely limited due to the degree of cementation.

In all five cases, the persistence of the NAPL exceeds the theoretical disappearance times calculated for a single contaminant and based on the observed properties of the fracture network and the matrix. This persistence appears to be due to an interaction of several factors, including replenishment of the NAPL over a significant period of time and high NAPL saturation. In addition, the NAPLs comprise a complex mixture of different components, thus field solubilities of all compounds are lower and the less soluble constituents are more likely to persist in fractures.

REFERENCES

Hardisty PE, Wheater HS, Johnston PM, Bracken RA (1998) Behaviour of light immiscible liquid contaminants in fractured aquifers, Geotechnique 48, 6:747-760

Kueper BH, McWhorter DB (1991) The Behaviour of Dense Non Aqueous Phase Liquids in Fractured Clay and Rock. Ground Water 29(5):716-728

Pankow JF, Cherry JA (1996) Dense chlorinated solvents and other DNAPLs in groundwater: History, Bahevious and Remediation, Waterloo Press, Portland, Oregon

Parker BL, McWhorter DB, Cherry JA (1997) Diffusive loess of non-aqueous phase organic solvents from idealized fracture network in geologic media. Ground Water 35(6):1077-1088

Ross B, Lu N (1999) Dynamics of DNAPL penetration into fractured porous media, Ground Water 37(1):140-147

Table 1. Summary of field observations

Lithology	Fracture types / spacing	Matrix properties	Contaminant	NAPL properties	Depth of NAPL penetration(m)	Time (years)
Alluvial clay	3 orthogonal sets (vertical and horizontal), 3 m spacing	V high porosity >0.4 Low K < 10^{-9} m/s Thick, plastic clay	Coal tar	D, viscous	> 8	30 - 50
Triassic sandstone	Infrequent vertical, ~10 m spacing, bedding plane 1 – 2 m spacing	High porosity 0.25 High K $5x10^{-5}$ m/s Also occasional beds of finer or coarser sandstone	Coal tar	D	38	>120
Weathered Triassic sandstone	Few, mostly bedding plane, occasional sub-horizontal	High porosity 0.25 High K 10^{-5} m/s Friable, weakly cemented	Coal tar PCE, TCE	D	7-12 (coal tar) dissolved phase only (PCE, TCE)	>100
Cretaceous sandstone	2 orthogonal sets, subvertical, 1 –2 m spacing	Moderate porosity 0.18 Low K 10^{-9} m/s Cemented pore throats	Gas condensate	L	33	20
Dolomite	2 sets of orthogonal vertical fractures, frequency decreases with depth from 10s cm to 10s m. Horizontal fractures above 15 m depth, frequent above 5 m.	Low porosity 0.03 Low K (not measured)	Unleaded motor fuel	L	7 - 9	>10 but shallow remediation after 5 years

Groundwater flow model for a disposal site in a granitic massif

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A b s t r a c t : The purpose of this project is to create tools for a detailed area investigation to select a potential site for a repository of high radioactive and heat-generating waste in crystalline rock. The problem is treated by Russian (VNIPI Promtechnologii, Mayak Chemical Combine) and German scientists (Deutsche Gesellschaft für den Bau und Betrieb von Endlagern für Abfallstoffe (DBE Tec), Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Gesellschaft für Anlagen- und Reaktorsicherheit (GRS mbH)). There exist two preselected areas to host repositories in the South of Russia: The first is located in the Ural near Mayak, the second in the center of Siberia near the Yenissey River. In the following the build-up of a groundwater model is demonstrated by the site "Nizhnekansker Massif" in Sibiria.

THE AREA

The area which is taken into consideration is situated in the Siberian Nizhnekansky hardrock massif between two little creeks which combine to the Kan River approximately 25 km east of the city of Krasnojarsk (Fig.1). The occuring rock is a very old granite complex and stems from the Precambrian basis. With approximately 3,500 km^2 it belongs to one of the greatest closed granite formations of Siberia. Thereby an area of 1,500 km^2 outcrops. In the consequence there had been long-term erosional processes which caused the genesis of an extended weathering zone composed of disaggregated granite. The depths of the granite amounts about 7 km whereas several stress zones are passed by. The investigated area is sized about 40 km^2 and contains a huge amount of fractures with different apertures.

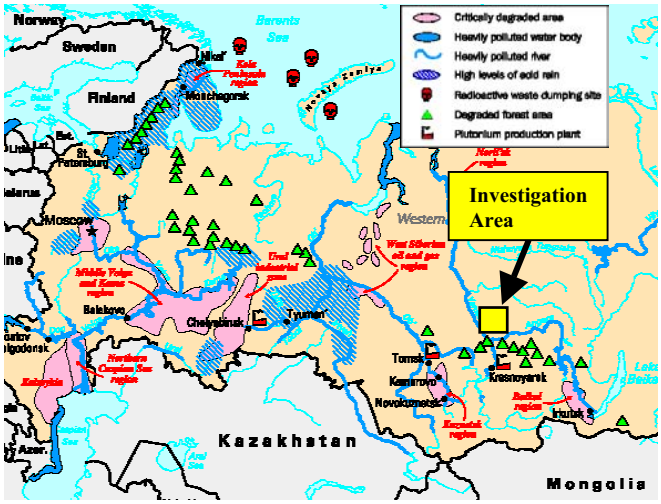

Figure 1. Location of the considered area

ESSENTIAL MODEL DATA

Unfortunately the amount of data available is rather sparse. So lacking data have to be compensated by expert knowledge. Resulting uncertainties have to be estimated and classified. Therefore it is very important to analyse the sensitivity of the different model parameters in order to know which parameter changes influence the result of the groundwater flow model and the subsequent transport.

Input parameters for the groundwater model are: the topography, boundaries of the different geohydrological layers, hydraulic head, groundwater recharge, location and slope of the fractures (three-dimensional) and the hydraulic conductivities of matrix and fractures.

Due to the age of the bare rock (over 570 Mio. years) and the erosion which took place all the time only flattened relief can be found. The altitude is between 250 and 440 above m.s.l. and smooth slopes are characteristic (Fig.2).

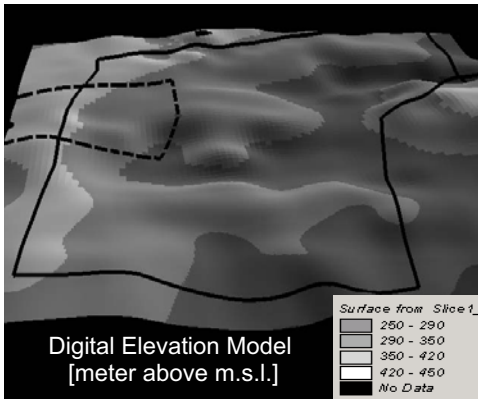

Figure 2. The digital elevation model (exaggerated by a factor 2, created by GIS) with the boundaries of the model (solid line) and the potential repository field (dashed line)

The rock complex is subdivided into two totally different water-bearing sections: A porous one near the surface and a fractured one in deeper layers. The porous rock complex consists of quarternary sediments and weathered granite. This layer is found in depths up to 50 meter below surface. It is accompanied by a fractured water-bearing zone. This layer was proven with drilling cores even in a depth of 2900 m. As a result of stress change of the rock complex there are a varying fracture density and fracture characteristic. All of these hydrogeological informations effect the groundwater dynamic of the whole system.

To find out the most suitable site for the potential repository different aspects are taken into account. The site must have the right extension to accommodate the radioactive waste. Furthermore it is very important that the site is far away from river systems and greater fractures and the existence of a phreatic divide is explicitly desired with respect to a small groundwater recharge.

Fulfilling these conditions and specifying a buffer zone of 500 m to the fractures it becomes obvious that only the part in the south-west of the investigated area comes into consideration for a potential radioactive waste repository. With regard to the boundary condition an area of about 11 km^2 is chosen for the investigated area. It is confined by fractures as well as the phreatic divide. The expected waste volume and the existing fractures determine on the area of the potential repository site. Therefore the area selected is sized about 1.5 km^2 having one half each inside and outside of the regional model area because it is situated on the top of the phreatic divide.

MODEL SET-UP

As a result of the conceptual formulation it was necessary to find a tool which complies with several requirements (Fig.3).

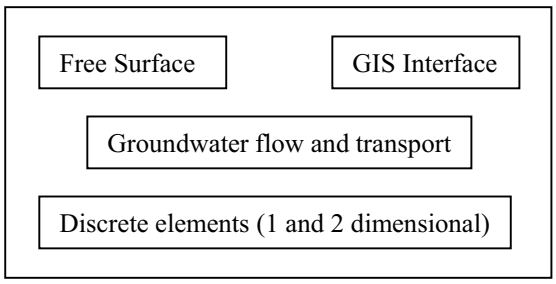

Figure 3 . Compartments of the groundwater model

These requirements are necessary for statements regarding to surface water effects, for implementation of the fractures in the model as well as to simplify the implementation of site-specific data so that it is not necessary to abstract them a second time. Thus the geological model is based as far as possible on real data. This is a very important point because the amount of data available is rather sparse. The rock itself is modeled with a porous-medium-approach. Finally this leads to a fractured/porous medium model.

For the description of the different layers as well as the potential repository site eight contour maps are necessary (Fig.4). The implementation of the geological layers is managed by data transformation based on the DEM in a GIS, a database program including a subsequent interpolation.

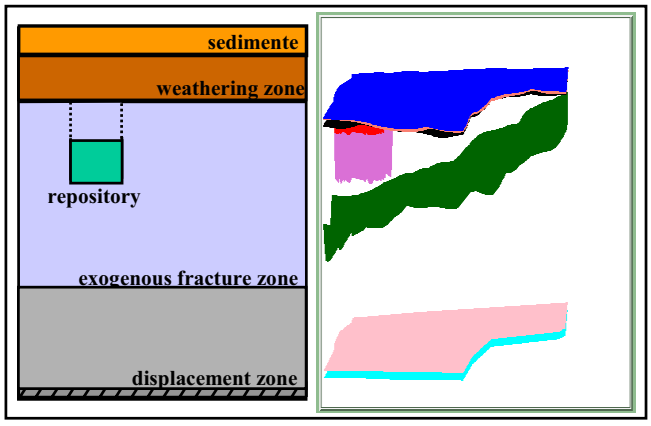

Figure 4. Schematical layers and their realisation (structure contour maps)

The produced model has an area of about 11.5 km^2 and a volume about 33 km^3. The regional model was discretised into finite elements. In the vicinity of fractures the grid is much finer than in the remote area. For each model layer about 15.000 finite elements are produced.

The next step was to assign the various parameters to the various layers. The data are taken from measurements of the Russian investigation program. The groundwater head is created and implemented according to the Russian data like the DEM. It also serves as boundary condition.

The hydraulic conductivity of the fractures and the matrix are also taken from the Russian measurements. The groundwater recharge which acts as input to the first layer is estimated on the basis of evapotranspiration and of the measured precipitation.

In the model 32 fractures are implemented with slopes of 90 degrees (Fig.5). They are discretised as two dimensional discrete elements. Therefore it is possible to give them independent apertures, hydraulic conductivities and other characteristics.

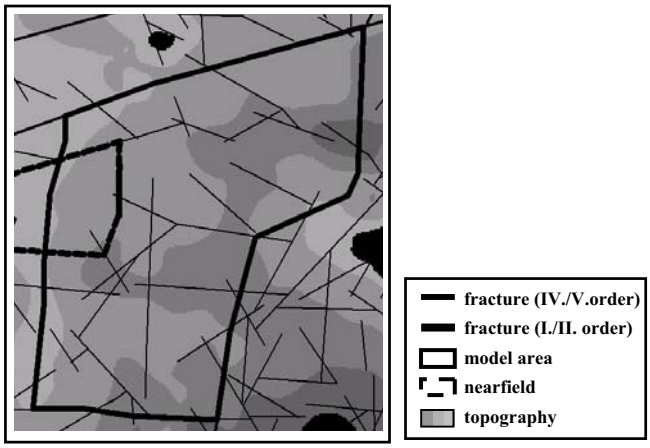

Figure 5. Model Fractures

FUTURE PROSPECTS

The groundwater model will be used as a basis of a transport model which allows to recognize the main transport pathways. In addition it will be possible to make some statements about the transport time.

A complete biosphere model will be established to get some information about the annual radiation exposure beyond the geo- and hydrosphere.

The model will serve as a basis for a long-term safety analysis with regard to radioactive waste disposal. Therefore it has been also decided to take into account the influence of heat on the groundwater flow.

So the whole investigations will help to formulate a methodology for a detailed site investigation and selection for a repository for high radioactive heat-generating waste in crystalline rock.

REFERENCES

VNIPI PT (2002) Standortdaten und schriftliche Mitteilungen

Anderson EB, Lyubtseva EF, Savonenkov VG, Shabalev S.I., Rogozin YuM (2001) The proposed geologic repository site at the Nizhnekansky granitoid massif near Krasnojarsk, Russia. 9th Internat. High-level Radioactive Waste Managment Conference, Las Vegas

Laverov NP, Omelyanenko BI, Velichkin VI (1994) Geologische Aspekte des Problems der Endlagerung radioaktiver Abfälle (in Russian), Geoekologya

Anderson EB, Dacenko VM, Kirko VI *et. al.* (1999) Resultate der komplexen geologischen Untersuchungen des Nizhnekansker Massives als Begründung für die Möglichkeit seiner Nutzung zur Endlagerung verfestigter radioaktiver Abfälle (in Russian) In: Untersuchungen der Granitoide des Nizhnekansker Massives zur HAW-Endlagerung (russ.), Chlopin-Institut, Sankt Petersburg

Methods of fractured aquifer characterisation using an example of a brittle fault zone in calcareous rock

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A b s t r a c t : Methodical approaches for the hydrologic characterisation of a brittle fault zone to be traversed in the course of tunnel construction are discussed. The application of hydraulic testing methods for the investigation of a fractured aquifer and the assessment of impact on a spa due to tunnel construction is shown using the example of a reconnaissance tunnel in the Lower Inn Valley, Austria.

INTRODUCTION

A highly transmissive fault zone was unexpectedly discovered during the excavation of a reconnaissance tunnel for the High-speed Railway Project Munich-Verona east of Brixlegg, Austria. The drilling of a rock anchor at tunnel position 2.27km caused a massive flow of water mixed with gravel into the tunnel. Continued drainage was not possible because of a possible impact on a health spa situated 600m west of the tunnel face (fig.1). In order to test the feasibility of sealing the aquifer, grouting was carried out in several sections. The sealing proved to be ineffective (Reichl *et al.* 2002) and therefore, an investigation program was initiated in order to assess the characteristics and the dimensions of the aquifer and the effects of drainage on the local groundwater regime.

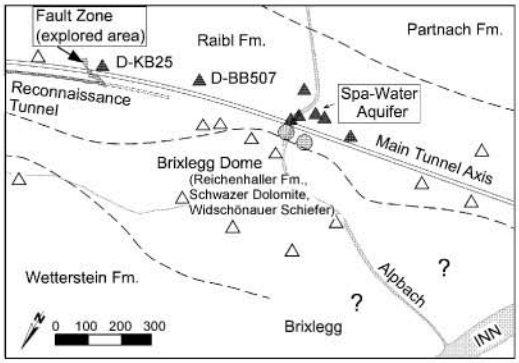

Figure 1. Sketch map of the project area. The locations of selected groundwater monitoring points are indicated by triangles and circles

Twelve (sub-) horizontal exploratory boreholes up to 70m in length were drilled both perpendicular to the tunnel axis and in the direction of the tunnel advance (fig.2). From the surface, additional vertical holes were drilled down to the elevation of the planned tunnel. The aquifer is attributed to a steeply dipping fault zone composed of a partially cohesionless fault breccia (Sausgruber and Brandner in press) up to 30m thickness intersecting the tunnel axis at a low angle (FZ1 in fig.2). A particular type of the fault breccia showed a primary porosity due to solution of gypsum and a secondary porosity due to its gravel/sand-type nature. A second fault zone (FZ2) was detected approximately 20m behind the first one. The repeated appearance of geological formation features and the general structural context indicated that the main fault zone was displaced along minor shear zones (sub-) perpendicular to the fault zone elongation. The waters of the fault zone showed a high degree of mineralization. As a result of intensive hydrochemical and isotopic analysis, a hydraulic connection between the water in the fault and the Brixlegg spa could not be ruled out. In view of the fact that further tunneling would only be economically feasible at a reduced groundwater pressure, a drainage experiment was conducted to evaluate the impact of groundwater draw-down on the nearby Brixlegg springs (fig.3, see also Reichl *et al.* 2003).

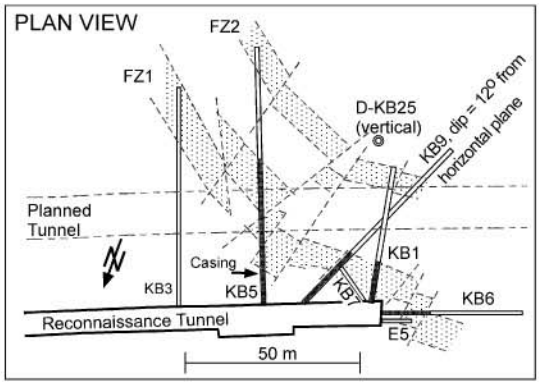

Figure 2. Borehole location at tunnel front and (interpolated) location of the main fault zones FZ1 and FZ2 (dotted pattern)

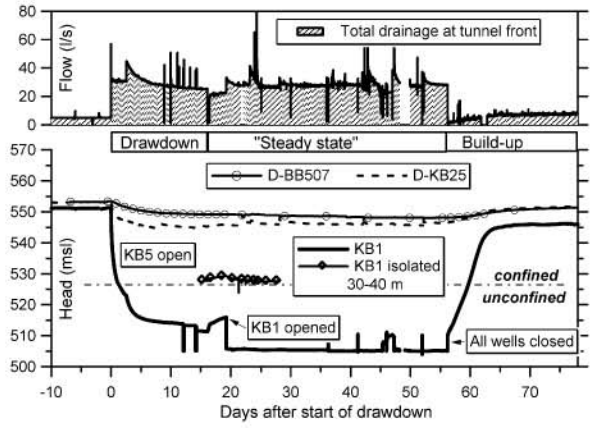

Figure 3. Draw-down test: drainage rate and pressure responses at various exploratory wells (locations given in fig.1 and fig.2)

INVESTIGATION PROGRAM

The main objectives of the investigation program were defined as: (A) Hydraulic and hydrochemical characterization of the aquifer system, (B) Evaluation of the hydraulic interconnection between the fault zones and the pressure distribution with respect to further tunneling and (C) Assessment of the draw-down related impact on the Brixlegg spa springs due to drainage around the tunnel. The investigation program included geophysical logging, geodetic and deformation measurements and intensive quantitative and qualitative groundwater monitoring, carried out from both inside the tunnel and from the surface within the area of the village of Brixlegg (Reichl *et al.* 2003). Ground water types were distinguished by content of $CaSO_4$, $\delta^{34}S$, and $\delta^{18}O$.

Double packer profiling

After the hydraulic head near the tunnel front was sufficiently lowered by 40 meters (corresponding to a pressure decrease from 4.5 to 0.5 bar measured at the borehole collar), hydraulic head profiles perpendicular to the tunnel were measured using a double packer system. The double packer was expanded at several positions along the uncased section of the horizontal exploratory wells (fig.2). The testing procedure included the measurement of the actual pressure head and the recording of the outflow rate and the pressure decrease in the test section after opening the test string valve. The head profiles along the monitoring boreholes indicate the extent of aquifer heterogeneity and the hydraulic interconnectivity between transmissive aquifer zones (fig.4). Transmissivity (T) and conductivity (K) values were roughly estimated assuming steady-state flow conditions (fig.5). The T/K-estimates showed that the conductive rock sections were not restricted to the principal fault zones FZ1 and FZ2, but were also found in the adjacent tectonically altered rock (marls, limestones, dolomites). In the course of packer profiling, electric conductivity (EC) and temperature were measured (fig.5) and formation specific water samples were taken.

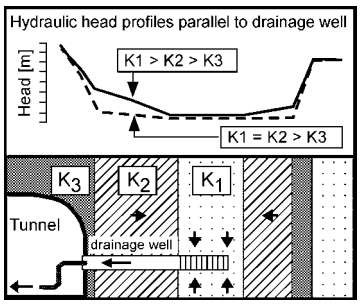

Figure 4. Schematic sketch demonstrating the use of pressure profiles for the evaluation of aquifer heterogeneity and aquifer inter-connectivity

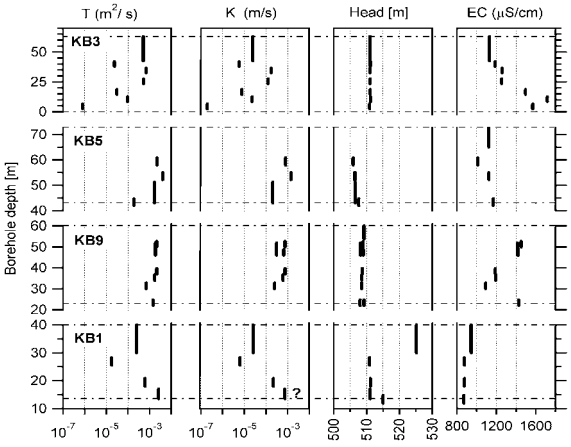

Figure 5. Results of packer profiling carried out in horizontal exploratory wells near the tunnel front

CONCEPTUAL AQUIFER MODEL AND RESULTS

Fast crosshole pressure responses suggested a good hydraulic interconnection of the two main fault zones FZ1 and FZ2. Evaluated head distributions and comparison of draw-downs in some of the horizontal exploratory wells suggested an aquifer composed of separated and in some cases isolated reservoirs (see borehole section 30-40m of KB1 in fig.5 and the conceptual model of fig.7). Within a transmissive "aquifer block", heads are similar and draw-down is controlled mainly by the (limited) recharge rate. The top of the high-K zone can be located roughly from the shape of the draw-down/build-up curves. The sudden flattening of the draw-down slope (fig.3) indicates the transition from confined to unconfined aquifer conditions. The head corresponding to the inflexion point in the pressure curve indicates the elevation of the upper boundary of the aquifer. The complementary effect was observed during the pressure build-up (fig.3).

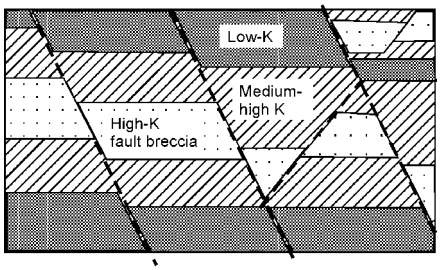

Figure 6. Schematic sketch (plan view) of high-conductivity fault breccias dislocated by late fractures. Adjacent rock sections show varying conductivity properties depending on the degree of brittle deformation

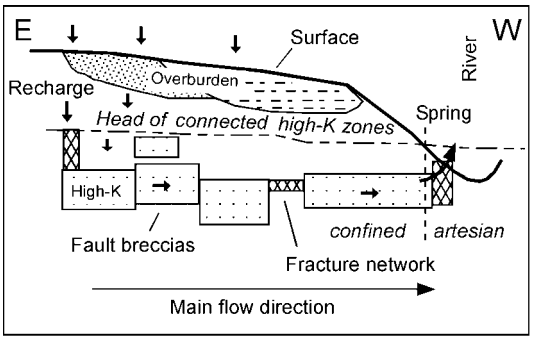

Figure 7. Conceptual model comprising high-K aquifer "blocks" connected by a late fracture system (see also fig.6)

Pressure responses during draw-down test were observed along a longitudinal zone comprising the fault zone near the reconnaissance tunnel and the Brixlegg spa (fig.1, full triangles). The occurrence of highly mineralized water is mainly restricted to the same area. The spa was significantly affected by the draw-down test, in contrast to other nearby springs showing a different chemical composition.

CONSEQUENCES FOR FURTHER TUNNEL ADVANCE

Further tunnel advance must account for several transmissive reservoir-like fault zone aquifers over short distances. The pressure conditions across two reservoirs may be similar or different, depending on the existence/condition of hydraulically connecting features (e.g. lateral sub-faults). Exploratory drilling in the direction of tunnel advance is an important measure during further tunnelling in order to prepare appropriate excavation techniques. Since draw-down effects turned out to be mostly reversible, further tunnelling is economically feasible if all the relevant supporting construction measures (e.g. controlled draw-down) and a lining which can sustain the full water pressure are installed.

REFERENCES

Reichl I, Mammel R, Kech M, Poscher, G, Fisch HR (2003) Temporary artificial draw-down of a joint aquifer. This volume

Reichl I, Wollmarker R, Stadler G, Schretter K, Eder S (2002) Erkundungsstollen Brixlegg Ost, Beispiel für die Grenzen der Wirksamkeit von Felsinjektionen. Christian Veder Kolloquium Graz Austria - Proc 17:177–s192

Sausgruber T, Brandner R (in press) The relevance of brittle fault zones in tunnel construction – Lower Inn Valley Feeder Line North of the Brenner Base Tunnel, Tyrol, Austria Mitt der Österr Geol Ges 94, Vienna, Austria

Assessment of free groundwater hazard in tunnelling: use of stochastic fracture network simulation and homogenisation

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A b s t r a c t : Tunnelling in crystalline rocks often face difficulties related to the presence and flow of free water in fractures. The 53 km long tunnel of Maurienne-Ambin which is planned at great depth for a future high speed railway to cross the Franco-Italian Alps, will meet a very complex geological architecture. For security and economy of this project, it is essential to understand deep-water movements. A first access gallery is presently under work in the Modane area (Savoie). It is crossing two main types of fractured rocks: quartzite and micaschist, with contrasted structure and hydrogeology. In both formations, stochastic fracture networks are simulated based on borehole data analysis in order to study the possible connections between the main conductive faults. Two methods for homogenisation are then tested to compute the flow in the neighbourhood of the gallery with a predictive intention. Validation attempts could be performed by inflow measures in the gallery.

TUNNEL PROJECT AND WATER

Deep tunnels in alpine regions may face to severe hydraulic conditions (high pressure and flow). Ground water, if present in large volumes and capable of free movement, presents a major hazard in tunnelling. In addition, penetration by ground water of many kinds of altered or closely fractured rocks promotes swelling, disintegration, or lubrication that produces capabilities in these rocks of slow to very rapid movement into a tunnel opening, greatly increasing the difficulty of the tunnelling operation. It is essential that in planning for a tunnel every attempt should be made to identify the location and size of bodies of underground water whether concentrated in fissures or dispersed through masses of porous and permeable rock.

The Ambin tunnel (53 km) from St-Jean de Maurienne (France) to Susa (Italy) will be the main new structure of the Lyon-Torino high speed railway link project. Excavation work will start from the two heads but also from three intermediate points, 300 m to 400 m under topographic level, at the ends of three inclined galleries. One of these galleries, which will be 3,8 km long, is presently under work in the Modane area (Savoie, France). In this area are planned underground fixtures, which are primordial for the project. These fixtures, as well as the tunnel, will be located under the hydraulic bottom level of the river Arc.

There, pumping capacity must be designed in order to face in-rush of water during underground works and to evacuate water up to the surface. Later, to forecast the dewatering flow rate is important for the exploitation of the tunnel. Hence, for security and economy of this project, it is essential to understand deep water movements. In the Modane area, the available data are mainly from a series of 21 drillings with few hydraulic tests.

Estimation of the amount of water and the location of heavy ground-water flows that might be encountered during a tunnelling operation is very difficult, especially in areas of considerable geological complexity. In fractured rocks, diffusivity along hydraulic pathways (the ratio of conductivity to storativity) varies considerably in space. Here we focus on free water or water of percolation capable of moving along open fissures through rocks under a hydrostatic head, since it is the cause of most major problems associated with water in tunnelling operations in fractured rocks.

HYDROGEOLOGICAL MODEL

Two lithological units are distinguished: a quartzitic unit, which is structured in peel thrusts, lies above a micaschist unit structured in overfolded strata. The detachment level corresponding to the Permo-Triassic transition allows for structural independence between these two units.

The two units were together subjected to a late tectonic, successively of N-S extension (opening of the Arc valley) resulting in an overall tilting of the structures southwards, NNW-SSE compression which modified again the dips of main structures, and finally, present ESE tension shear.

The hydrogeological model has been defined by combining seismic, hydraulic, chemical and thermal logging data (Fabre *et al.* 1996).

Well logs and seismic were recorded in eight deep boreholes (length > 500 m), providing a rich structural database. The study of amplitude of seismic arrivals allowed to detect trapped high pressure water. Three types of aquifer have been recognised (Monin 1998): a superficial aquifer with rapid water flows, a middle aquifer where water flows slower with depth, and a deep one where mineralised water is trapped along NE-SW faults, spaced about 50 m.

In the quartzite formation, some boreholes showed hydrochemical evidence of flows in fractures connecting with the earth's surface and fed by water from streams or standing bodies of water. Near to the west end of the gallery, three boreholes exhibit some interference in water head variations. Thus, the quartzite aquifer contains young and cold water of meteoric origin. The destination of this fast water flowing is still unknown. This question is addressed following the methodology presented in Fouché and Lacquement (2001).

Well logging and packer tests have shown that the micaschist have a permeability at least 10 000 times lower than the quartzite, with old mineralised water from the Alps basement. Some transmissive zones were encountered, probably related to the NE-SW faults. Whether these faults are connected or not depends on fluid flow through the pervasive network of lower order fractures.

We attempt to model the contribution of lower order fractures to the water inflow hazard during underground works. The difficulty resides in the extrapolation of punctual data to the scale of a complexly deformed rock mass. Our model employs a stochastic and discrete fracture network approach (see Fouché *et al.* 2002) to represent transmissive fractures in the rock mass explicitly.

STOCHASTIC FRACTURE NETWORK

Some fracture sets were identified through delineation of clusters on stereoplots of actual fracture orientations measured in three deep boreholes.

A geometric model of the network is constructed using the Fraca software (http://www.beicip.com), which honours the observed fracture intensity and orientation distributions, with location of fractures (rectangles) represented by a Poisson point process. Size distribution of fractures is first estimated through an empirical relation with the width of fracture infill (Fouché *et al.* 2001) and then tuned through a parametric study.

Stochastic sampling of these fracture sets, each fracture being represented as a rectangle with metre to several decametre order size, produced a dense network as shown on Fig.1.

The transmissivity was measured only in some highly transmissive zones during short-duration single borehole tests and, consequently, did not investigate a large volume of rock. These results give a maximum value for local fracture transmissivity. This parameter is supposed to take any lower value according to a probability distribution which is likely to be of log-normal type but poorly constrained. We suppose that all the fractures visible on the BHTV logs are potentially transmissive.

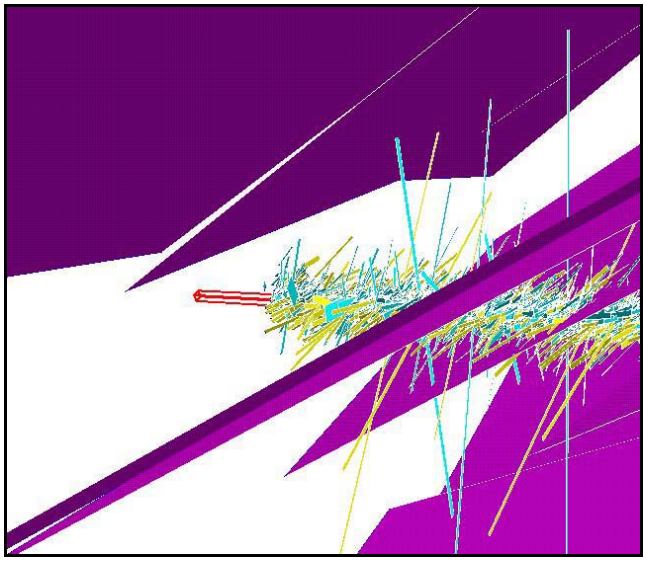

Figure 1. Horizontal 3D view south-westwards in the micaschists: large and dark planes are NE-SW conductive faults, hundreds of meters in size and quite regularly spaced (about 50 m), that could be connected by some transversal random fractures. Only are displayed (light colours) the fractures that intersect a virtual domain (a 5 m × 5 m square column), the left end of which is visible

EQUIVALENT PERMEABILITY

The equivalent permeability in local cells of the fractured rock mass and the matrix block dimensions of an equivalent homogeneous model cannot be easily derived from observation.

As a first method, a tensor of equivalent fracture permeability is derived from single-phase steady-state flow computations on the actual fracture network using a 3D resistor network as described in Bourbiaux *et al.* (1998).

But in the known methods used for the determination of the hydraulic behaviour at large scale (here more than 50 m) of rock masses, based on the simulation of flow in a fracture network, the mean flux and the mean pressure gradient in the network are not rigorously determined. We follow a new method for deriving these quantities in a heterogeneous permeable block, from pressure and flux values on the boundary of the block. Based on the condition of linear variation of pressure on the block boundary, a block conductivity tensor was defined by Pouya and Courtois (2002). It has been shown that this tensor is symmetric and positive-definite.

This double approach, based on explicit and homogenised fracture network, should lead to a better understanding of the hydraulic behaviour of the rock masses around the tunnel and to a better informed decision regarding the appropriate remedial measures, for instance design of a pumping capacity.

REFERENCES

Bourbiaux B, Cacas M-C, Sarda S, Sabathier J-C (1998) A rapid and efficient methodology to convert fractured reservoir images into a dual-porosity model. Revue de l'Institut français du Pétrole 53(6):785-799

Fabre D, Goy L, Menard G, Burlet D (1996) Température et contraintes dans les massifs rocheux: cas du projet de tunnel Maurienne-Ambin. Tunnels et Ouvrages Souterrains 134:85-92

Fouché O, Alfonsi P, Chantron L, Durville J-L (2002) Des forages à la simulation mécanique des massifs rocheux, l'apport d'une approche probabiliste 3D des réseaux de discontinuités. In: Optimisation de l'insertion des ouvrages dans le sol et le sous-sol - Actes des Journées nationales de Géotechnique et de Géologie de l'Ingénieur, Nancy, France, Oct 2002, CD-Rom

Fouché O, Cojean R, Arnould M (2001) Caractérisation géologique et géométrique de la fracturation naturelle d'une formation granitique à partir de carottes de forages. Bulletin of Engineering Geology and the Environment 60(3):231-240

Fouché O, Lacquement F (2001) Structural control on hydraulic connection through the Poitou basement and the contact with its sedimentary cover. In: Seiler Klaus P, Wohnlich S (eds) New Approaches to Characterising Groundwater Flow - Proc XXXI Congress of the IAH & ATH, Munich, Germany (supplement)

Monin N (1998) Caractérisation par sismique de puits d'un aquifère profond: cas de la zone des aménagements souterrains de Modane (tunnel de base, liaison ferroviaire Lyon-Turin). PhD, Université de Savoie, 166 pp + annexes

Pouya A, Courtois A (2002) Définition de la perméabilité équivalente des massifs fracturés par des méthodes d'homogénéisation. CR Geoscience 334:975-979

Hydrogeological analyses and modelling of water resources of the Gavorrano mine, Italy

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A b s t r a c t : Hydrogeological problems linked to the groundwater level rebound and the water storage in the mine of Gavorrano are described. In particular the results of a study concerning circulation, quality, discharge and re-utilization of mine water are reported. It is shown how the geological settings of the area control the water quality, chemistry and discharge. Water rebound is analysed on the basis of available historical and recent and new data both for its hydrodynamic influence and the consequences on water resources. Attention is placed on water characteristics, trying to highlight the different water circulations, the mixing and chemical changes within the excavated rock masses and their relationships with surficial aquifers.

INTRODUCTION

Mine water drainage is a problem during mining as well as after mining activities and dewatering by pump are completely ceased. Mine workings act as a drainage and percolation system so that the water rarely can return to its original conditions and circulation path. Water level recovery after exploitation causes different problems concerning the stability of underground openings but especially the environment and the reconstitution of groundwater resources. If no acid drainage is produced, the presence of toxic elements, metals or salts could exclude the uncontrolled discharge of these waters and their use for different purposes. At the same time, the recovery and re-utilisation of mine drainage waters show some very interesting aspects, especially where increased water resources are required because of increasing demand.

The Gavorrano mining complex was the most important one in Europe for the extraction of pyrite (used mainly in the chemical industry) and it had its major development period in the 1940-50's and closed down in 1982. At present, some of the drifts and lift systems are in perfect working order, in the central part of the mine (Roma and Impero shafts), up to a depth of 143 m b.s.l. (over 400 m from the surface). All other entrances and shafts have been closed for the dewatering and safety operations and the mining system is over 5 km long, 450 m deep, with an exploitation thickness of over 500 m.

HYDROGEOLOGICAL ANALYSES

The Gavorrano mining area is located in south-western Tuscany, within the Metalliferous Hills (Colline Metallifere) a few kilometres from the Thyrrenian sea.

Typical of this tectonic province are intrusive bodies, with decreasing age from west (7-8 My) to east (4 My), which emplacement was following by more extension. The Tuscan geological series (Triassic-Oligocene) is overlaid by the Sub-Ligurian and Ligurian Units. The Tuscan series outcrops entirely in the Gavorrano area together with a Pliocene (4.9-+0.15 My) quartz-monzonitic intrusion, oriented NNW-SSE. The sedimentary sequence is mainly represented by the Calcare Cavernoso, a brecciated and karstified limestone (Noric). The Cavernoso appears partially metamorphosed at the contact with the intrusion, covered by the Avicula limestone, dolomitic limestone and marl (Rhaetic). The Liassic Calcare Massiccio follows in the series with massive limestone and a peculiar brecciated facies.

The pyritic ore was cultivated in lenses or masses of irregular shape at the contact between the intrusion and the Calcare Cavernoso, and sometimes along the main faults, as well between

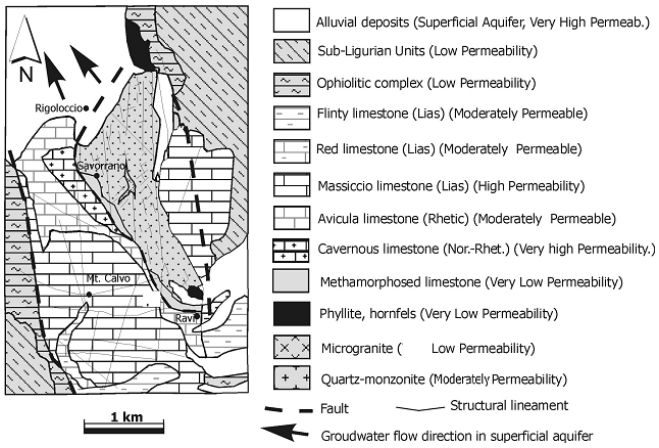

Figure 1. Hydrogeological map of the Gavorrano area

the phyllites and the Cavernoso. The intrusive body is limited by two normal faults to the eastern (45° dip) and the western sides (60° dip). The limestones are extensively karstified both at the surface (dolines, lapies or karrens, lapies wells, caves, etc.) and in depth.

The attribution of a hydrogeological class (in Fig.1) to each of the geological formation has been done by considering the observed lithology, the degree of fracturing, the degree of weathering and alteration, the presence of karstic structures, both at the surface and within mine drifts. Geomechanical analyses and infiltration tests were carried out in some representative sites. The coefficient of potential infiltration for the carbonate rocks have been estimated within the range from 8.7 to 10 L/s/Km^2 as a function of the increase in fracturing and karst conduits. Lower values of the coefficient can be attributed to the intrusive rocks (changing with the degree of fracturing and weathering) and to the flyschs. Average annual rainfall in the area amounts to 800 mm with an average evapotranspiration of 430 mm/y. The rainy season lasts from October to February with the maximum average monthly rainfall in November (120 mm) and very low precipitation in summer (20 mm in July). A final consideration concerns the eventual permanent changes in hydraulic properties (conductivity and transmissivity) due to mining. An useful research of the mine documents and mapping has been carried out.

Water rebound

The control of groundwater rebound, in progress at the Gavorrano mine since August 1995, is regulated by a submersible pumping systems. These systems consist of two pumping points immerged in the Impero Shaft and the Roma shaft respectively and a new

pumping point (Rigoloccio shaft 3). A deep borehole was recently drilled to increase the monitoring system of the water levels (where the piezometers are too near the surface) and to identify the lithological and mechanical characteristics of the terrains near the Bagni di Gavorrano Village. The results of the mechanical soundings are in contrast with previous geo-structural analyses and the geophysical results because of cavernous limestone is less permeable than elsewhere, with few and closed fissures, few cavities, even though scarce in gypsum levels. However the possibility of local and important fractures or small faults is not to be excluded. More information will be collected by geoeletric or by new soundings in order to set up a monitoring system. For all these reasons too, before carrying out further drillings, it was decided to re-open a shaft near Rigoloccio in order to reach the tunnel (up to –200 m.b.s.l., which connected the Rigoloccio mine with the Gavorrano one (Roma shaft), and then intercept the waters, analyze them and install a new pumping system. An initial analysis has shown that this operation could produce good results, not only for the control and the safety of the water rising operations, but also for the separation, albeit not total, of the hot and cold waters infiltrated in Mt. Calvo (limestones).

Groundwater level rebound can be understood starting from the data recorded during the water level lowering, and some occasional or accidental water rising (arrest of water pumping in 1944-45, because of the passage of the Second World War front). The waters pumped from the tunnels have a complex origin. It is present a surface circulation, due to the infiltration in fractured and karstfied carbonatic rocks, and a deep circulation of thermal water. The latter sulphate-calcic water, with a temperature of almost 40°, were cut off and deviated during the mining activity of the pyrite, and mixed with the other groundwater pumped out. Since 1995 the pump discharge remained almost constant at 60-65 L/s with exception for two periods of heavy rainfall. This allowed the storage of about $300*10^3$ m^3 of water (Crosta and Garzonio 1998. By means of the data recorded during the two phases (1997, 1998) of increased discharge it has been possible to perform a recession analysis which gives us a good insight into the aquifer structure. According to the recession analysis the average water resources that are renewed yearly amounts to 2.1 Mm^3 or 66 L/s. These values are quite comparable with the average yearly pump discharge (60 L/s or 2.08 Mm^3). Finally, by comparing these data with those obtained by the effective infiltration analysis (1.1 Mm^3) it results that yearly almost 1 Mm^3 of hot water is regurlarly flowing from the deep circulation system into the mine. Furthermore, because of the almost constant temperature of the pumped water it can be assumed that the hot water discharge grows together with the fresh karstic water discharge during wet periods maintaining an almost constant ratio between the two.

Water chemistry

A further series of samplings was performed over the last four years to complete the data set already available. In particular in 2001, 2002 and February 2003 some new water sampling campaigns were carried out to verify the possibility of a variation in the chemistry of the pumped water, after the setting up of the new pumping system in Rigoloccio shaft 3. The mine water samples can be clearly divided into two main groups: "superficial" bicarbonate waters (from levels +240 m a.s.l., +155m: Mg-Ca, +90 m: Ca-Mg-HCO_3) and deep sulphate waters (Ca-Mg-SO_4, -80 m b.s.l., -110 m, -140 m, -200 m). This grouping can be done on the basis of the sulphate (from sulphide oxidation and evaporites solution), iron and silica contents and it is also suggested by the few temperature data, even if more qualitative observations were made. In fact, by fitting temperature measurements, excluding samples taken at the outlet of the drainage tunnel (1.5 km long), a geothermal gradient of about 75°C km^{-1} was obtained in agreement with Baldi *et al*. (1995). All the other sampled waters generally presented values just a little over neutral (7-8). Mine drainage is characterised by an average temperature of 32°C, a 7 to 8 pH value probably as a result of temporal changes and the mixing action caused by pumping.

Isotopic analyses

Mine waters were analysed in three different campaigns (1995, 2001 and 2003) to determine the ^2H, ^{18}O, ^3H, and ^{13}C content. These samples were collected from a dripping stalactite (-140 m b.s.l), from the drainage pipe system at –140 m. b.s.l and at the drainage tunnel outlet (+70 m a.s.l and Rigologgio shaft). From the ^2H vs ^{18}O plot (fig.2) it is observable that data points are aligned and lay within the interval delimited by the standard world precipitation line ($^2H = 8*^{18}O+10$) and those presented by Zuppi (1986; $^2H= 8*^{18}O+15$) and by other authors for the Thyrrenian and Mediterranean regions. Hence, waters don't show any fractionation of isotopes as occurring for geothermal fluids and are comparable with those of the regional recharge suggesting homogenisation due to the length of the flow path in the fractured rocks. The sample taken from the stalactite show a slightly higher ^{18}O contents, and for this reason it could be considered a deep water on the contrary of the other two samples. The Tritium content is quite constant and this could be the result of a long circulation time or of a very short one. Previous considerations about ^2H and ^{18}O contents, water chemistry and some published researches make more probable a residence time of about 15 years or more. The contribution of more surficial waters can then be read by the increase of tritium content in the drainage samples. The isotopic composition of the total solute carbon is one more step in the definition of the state of water equilibrium. Again , the other two sample are characterised by a different trend suggesting mixing of different waters (drainage water at -140m) and a surficial contamination (drainage tunnel) . The equilibrium of deep waters is also suggested by the over - saturation both in the carbonate mineralogical phases and gypsum.

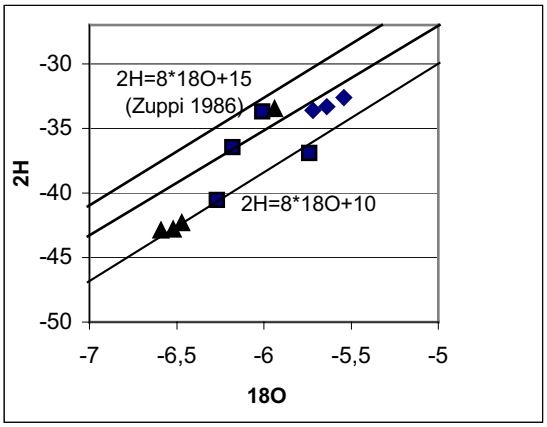

Figure 2. Plots of ^2H vs ^{18}O

REFERENCE

Baldi P, Bellini S, Ceccarelli A, Fiordalisi A, Rocchi G, Squarci P, Taffi L (1995) Geothermal anomalies and structural features of southern Tuscany (Italy). Int Inst Geotherm Res Papers, World Geothermal Congr., Florence, May 18-31/1995:7-11

Crosta G, Garzonio CA (1998) Engineering geology problems in the closing down of mining areas II: Hydrogeological problems of mining rehabilitation. In: Sivakumar M, Chowdhury RN (eds) Proceed Environmental Management, Pergamon, 2:1153-1162

Zuppi GM (1986) Introduzione all'idrologia isotopica. In: Zavatti A (ed) Proc Conf on Ambiente Protezione e Risanamento, Pitagora Ed, 1:281-335

The hydrogeological consequences of reduced groundwater levels after tunnel constructions

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A b s t r a c t : The consequences of groundwater leakage after tunnel construction include effects on foundations, groundwater supply wells, lakes and vegetation. The vulnerability depends on a combination of local geology, hydrology and vegetation. The amount of accepted leakage can, to a certain extent, be evaluated from the water balance equation and a site survey on site vulnerability (existing drainage, wetland vegetation, topography, and quaternary deposits). This paper presents the experiences from a selection of tunnels excavated in Norway during the last 40 years. Examples of damage to nature are given. In tunnels constructed during the last 5-10 years thorough pre-investigations followed by adequate precautions have drastically reduced the leakage problems.

HISTORICAL BACKGROUND

Norway is probably one of the countries with highest construction of tunnels compared to the population. There is a long tradition in construction of tunnels for hydropower plants as well as for roads and railroads. The first subway of Oslo constructed more than 100 years ago caused severe damages of several houses founded on clay. After that there has been awareness for the consequences of tunnel drainage in urban areas.

There has, however, been little attention to other type of damage as reduced groundwater supply from local wells and damages to natural habitats. In some regions, fairly large consequences of tunnels can be seen. Drainage patterns above water transport tunnels for hydropower plants in Vinje municipality in Southern Norway was mapped in the late seventies (Samuelsen 1979) a few years after the construction of the tunnels. Today the area has changed permanently to a dyer landscape. Another damage was caused by a drinking water tunnel through a hill in the outskirts of Oslo. A small lake commonly used for bathing and leisure suddenly disappeared, as the tunnel was excavated along a well-known fracture zone. None of these incidents caused major protests from the public opinion.

During the next 20 years the pubic awareness of the nature gradually increased. In the beginning of the 1990s the railway tunnel "Romeriksporten" to the new Oslo airport drained a small pond in the middle of the forest east of Oslo. The water level in one of Oslo's reserve drinking water reservoirs, Lake Lutvann, was also temporarily lowered. This caused an unforeseen public reaction, and huge efforts and a lot of money had to be spent stop the inflow of water. After this incident thoroughly pre-investigations have been carried out for almost all tunnel projects. Pre-grouting in fractured areas commonly prevents the largest water inflows, and grouted fractures of several centimetres widths are often seen in unlined tunnel walls. However, large inflows of water are still occasionally reported.

One of the important tasks for the pre-investigations is to predict the acceptable amount of leakage to the tunnel. Geological, hydrological and biological factors have to be considered to evaluate this issue. The objective of the work presented is to present some cases studies where this evaluation has been carried out in Norway.

GEOLOGICAL FACTORS

Tunnels in Norway are excavated through a variety of rock types: Precambrian basement, Caledonian thrust nappes, Cambro-Silurian sedimentary rocks, and Permian intrusive and extrusive rocks. All these are crystalline rocks mainly without primary porosity. However, as far as leakage to tunnels concerns, their hydrogeological characteristics vary widely.

In Precambrian rocks the fracture systems seems to be crucial for both water leakage as well as several other excavation problems. Large water inflows from certain fractures are experienced in tunnels even at depths several hundred meters below the surface. The progress of the Romeriksporten tunnel was almost stopped because of an inflow of water from fracture systems well known to be very permeable. We have less experience from tunnels in Cambro-Silurian sedimentary rocks, but fractures with high water conducting capacity seem to be less common.

Tunnelling in the Permian Oslo Region has met a series of problems in connection with water inflows form volcanic extrusive rocks with interbedded sediments. Dykes of intrusive rocks cause even larger water problems. There are several remnants of Permian cauldrons in the Oslo region, and, in spite of their age, the ring dykes (often syenites) of these structures can cause large inflows of water. A new tunnel for the Norwegian highway RV 35 was excavated after quite thoroughly pre-investigations. Part of the tunnel was driven in Cambro-Silurian rocks without any problems. The excavation in Permian lavas and the central pluton of a cauldron remnant caused water leakage, but no more than could be handled. However, when the excavation reached the border of the cauldron, they probably burst into a small part of the primary ring dyke and the water flew in at a rate of more than 4 m^3 per minute.

Parts of Norway were inundated after the last ice age, and some low laying areas are now covered with marine clays of low permeability. These clays may seal the fractures in the bedrock, and partly prevent leakages from lakes and rivers to tunnels.

In mires (peat lands) lowering of the water table can cause irreversible settlements. Peat formations partly floating on lakes and groundwater fed fens areas are most vulnerable. The drainage of the small lake above the Romeriksporten tunnel also caused a small landslide. Tilting trees can bee seen after reduced groundwater levels on peat land forests.

In areas with crystalline bedrock the infiltration- and storage capacity of the superficial deposits is crucial for the water supply to vegetation in dry periods. In Norway marine clays and glacial deposits often delay drainage to groundwater reservoirs in the bedrock. Thus the vegetation can be less vulnerable if the groundwater level is lowered.

HYDROLOGICAL FACTORS

Leakage to a tunnel changes the groundwater flow above the tunnel. This may cause changes in the water balance including consequences for the water level in lakes and reduced humidity in

forests and arable land. Finally the consequences may be reduced growth and changes in the fauna to less moisture and groundwater demanding species.
General water balance equations are

$\mathbf{P = E + Q + I}$ $\qquad$ $\mathbf{I = SW + GW + L_T}$

P = precipitation
E = evapotranspiration
Q = surface runoff
I = percolation

SW = runoff to water courses
GW = percolation to deep groundwater
L_T = leakage to the tunnel

Leakage to tunnels often increases the hydraulic gradient resulting in a potential increased percolation from traditional, discharge zones as bogs and small ponds to the groundwater reservoir. The result will be reduced surface run off, and sometimes reduced humidity in the soil.

The hydrological consequences of drainage to a tunnel are influenced by several conditions.

- Size of catchment area compared to vulnerable lakes and mires
- Topography
- Hydrological conditions (e.g., precipitation excess)
- Groundwater gradient towards the tunnel
- Existing soil moisture storage and plant moisture requirement during droughts (the plant roots possibility to reach the groundwater or the capillary zone before and after the drainage).

In the planning of the highway RV 35 tunnel mentioned above, the drainage of Lake Langvann was regarded as a possible problem. The tunnel passes just underneath the lake, as shown in fig.1. An evaluation of the drainage areas and the possibility for leakage partly changed this view. Tab.1 presents the probable leakage compared to the runoff (precipitation excess) for each drainage area, as it would have been if the inflow were limited to 10 L/min/100 m tunnel. The table indicates that if the leakage is the same along the tunnel, Lake Langvann is less vulnerable for drainage than some of the smaller lakes and bogs.

BIOLOGICAL FACTORS

The consequences of drainage to a tunnel depend on the natural selection of plants and animals. Vegetation with shallow roots is commonly not influenced unless the groundwater level is near the soil surface. On the other hand some mire vegetation totally depends on a high groundwater level and is thus vulnerable for any drainage. Also, fen vegetation often depends on nutrient rich groundwater. Vegetation in steep hillsides is rarely influenced by drainage as the groundwater level here is commonly well below the surface.

Drainage of agricultural areas may cause economical consequences, even though the direct effect of the drainage sometimes is difficult to observe. Drainage to a tunnel of the surplus snowmelt water may reduce the superficial groundwater storage resulting in reduced soil moisture storage. Consequently, water deficiency would occur in potential dry summer periods.

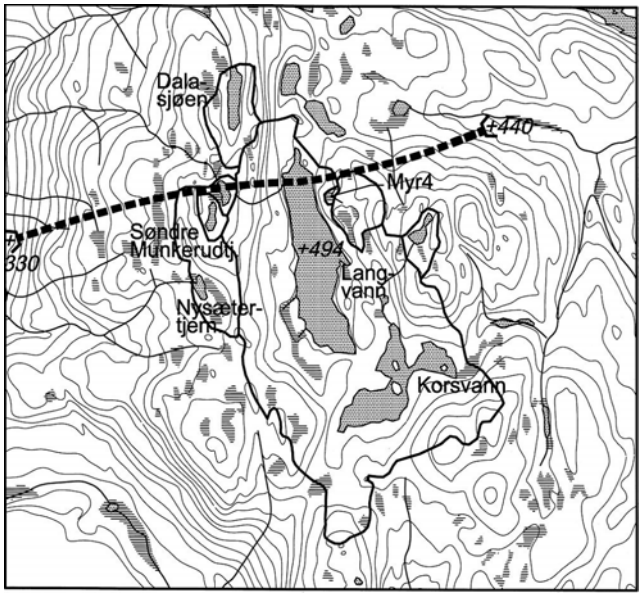

Figure 1. The RV 35 tunnel. Drainage areas in the hydrological assessment
Dark lines indicate borders of catchment areas.

However, in areas with high groundwater level and poor tile drainage, tunnel drainage may also favour the growth of agricultural plants.

Generally moderate groundwater drainage will be of less importance for the animal life, as the influence area of a tunnel is limited. Exceptions can e.g. occur in dry hillsides where the humidity in deep clefts caused by fractures in the rocks is crucial fore reproduction of insects.

LEAKAGE CRITERIA

Hydrological evaluations could be used to evaluate leakage criteria to protect nature areas and surface waters vulnerable to groundwater drainage. Leakage criteria could e.g. be given as acceptable leakage per minute per 100 m tunnel. For wells, flow within a single fracture system can be dominant. It could therefore be difficult to express maximum leakage criteria in terms of a certain volume of water per metre run of tunnel.

REFERENCES

Samuelsen JM (1979) Hydrogeologic maps Tryveli Bordalsvann and Hyljeli Vennemo, Vinje municipality. Norges landbruksvitenskaplige forskningsråd, Styringsutvalget for jordforskning (Norwegian Agricultural Research Council)

Table 1. The RV 35 tunnel. Probable contributions from each catchment area if a total leakage of 10 L/ min/100 m tunnel

Catchment with Lake or bog that could be drained	Annual runoff from the catchment	Part of tunnel that can drain each catchment	Total annual leakage of the actual tunnel section	Probable leakage contribution from catchment	Probable annual leakage from catchment	Leakage from catchment in % of total run off
Lake Langvann	1 819 712 m^3	750 m	39 420 m^3	80 %	31 536 m^3	2 %
Lake Nysetertjern	189 646 m^3	300 m	15 786 m^3	20 %	3 157 m^3	2 %
Lake Søndre Munkerudtjern	25 463 m^3	500 m	26 280 m^3	40 %	10 512 m^3	41 %
Mire 4 (Myr 4)	4 179 m^3	100 m	5 265 m^3	30 %	1 580 m^3	38 %

Factors influencing bacteriological quality of groundwater in Norwegian bedrock wells

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A b s t r a c t : Field conditions have been examined around wells supplying groundwater to 50 Norwegian waterworks in order to identify possible causes for bacteriological contamination. Bedrock wells located in areas with substantial thickness of superficial deposits are less prone to bacteriological contamination of the groundwater Data indicate also that a well-house provides better protection against bacterial contamination compared with concrete well-protection. Improper design of the well casing may also lead to contamination, for example where the top of the casing doesn't protrude above ground level allowing inflow of surface water through leaks in the concrete well-protection. The importance of multiple barriers securing groundwater wells is also highlighted here.

INTRODUCTION

In Norway many small waterworks and private houses use groundwater derived from bedrock. In the late 1990s between 3000-4000 new wells were constructed each year, and 3.4-6.8% (Morland 1997) of the population was supplied with groundwater. Information from the National Institute of Public Health and various departments of the Norwegian Food Control Authority indicate bacteriological contamination in many of these groundwater wells, and the National Institute of Public Health consider requiring disinfection of all drinking water from these waterworks. A PhD-study was initiated in 1998 at the Geological Survey of Norway (NGU) with the aim to look at the vulnerability of groundwater wells in bedrock concerning bacterial contamination. Bacteriological analyses of raw water and tapwater from 195 waterworks in Norway have been carried out over a period of two years. The data show that 74% of the waterworks have registered too high heterotrophic plate counts or contamination by coliforms. The results have been summarised in Gaut *et al.* (2000).

Fieldwork was subsequently carried out at 50 of the 195 waterworks in order to identify the causes of the bacteriological contamination. It is assumed that the main factors influencing the bacteriological quality are: the amount of superficial deposits at the wellsite, design and protection of the well, the location of the well, the state of the pipeline and also the physio-chemical quality of the water. An analysis of some of these factors is presented in this paper.

DATA COLLECTION AND PROCESSING

In all, 74% of the 195 waterworks studied by Gaut *et al.* (2000) have problems with the bacteriological quality of the groundwater based on the national standard for drinking water quality of 1995 (Sosial- og helsedepartementet 1995). About half of them have only registered too high heterotrophic plate count (HPC). The other half has problems with either coliforms (Total coliforms (TC) and fecal coliforms (FC)), or both coliforms and HPC. Based on these results, field conditions for the wells of 50 of the 195 waterworks were more closely examined during the summer/autumn of 2000 and 2001.

A total of 148 wells have been examined with regard to the following parameters: design and protection of the well, amount and thickness of superficial deposits in the well area, land-use around the well, possible sources of pollution, and geographical location such as distance from the shoreline and location relative to the occurrence of marine sediments. (Marine sediments are currently found in Norway at elevations of up to about 200 m above sealevel ('marine limit') due to post-glacial isostatic uplift.) The data for each well have been examined in relation to the bacteriological quality of the water to identify possible causes for bacteriological contamination.

Unfortunately, bacteriological quality of groundwater exists for only 60 of the 148 wells examined, because several of the waterworks do not collect water samples directly from the supply well. Instead, they collect raw water in the vicinity of the treatment plant or pressure tank, or tapwater from the distribution line. Thus, the reported water quality in these cases represents an integrated value where the waterwork is supplied from more than one well. In addition, when the samples are tapwater the pipeline will affect the water quality. Waterworks with only one well have, however, been included in the interpretation, but the bacteriological water quality may not represent the quality of the groundwater in the well where the distance between the well and the sampling location is long.

Another limitation for the interpretation is the lack of certain data for some of the wells, such as well depth, length of casing or thickness of superficial deposits.

DISCUSSION OF DATA

The thickness of the superficial deposits has been evaluated at each wellsite and the value classified as 1) medium to thick, or 2) thin or discontinuous. Of the 35 wells situated in areas with medium to thick superficial deposits, 51.5 % (tab.1) have no bacterial problems. On the other hand, only 28 % of the 25 wells in areas with thin or discontinuous deposits have no bacterial contamination. This suggests that wells located in areas with significant superficial deposits are less susceptible to bacteriological contamination.

The number of wells without bacterial problems appears to decrease with decreasing thickness of the superficial deposits at the well location (tab.1). Where the deposit thickness is more than 5 m, 54-66 % of the wells are without bacterial contamination, whereas this number drops to only about 30 % of the wells when the depth to the bedrock is 5 m or less. This again shows the importance of placing bedrock wells at locations where the superficial deposits are substantial.

Table 1 shows that 47 % of the wells are without bacteriological problems when located below the marine limit, against 30 % of the wells above the marine limit. Thus, wells situated above the marine limit appear to be more vulnerable to bacteriological contamination. This result is further compared with the extent and thickness of the superficial deposits (categories 1 and 2) in the well areas. Below the marine limit most of the wells are situated were the superficial deposits are medium to thick and 61.5 % of these wells have no bacterial problems. Above the marine limit, the well locations are about equally distributed between the two categories. But, in this case, more wells located in category 2 (thin or discontinuous) have no bacterial problems compared with

Table 1. Number of wells with or without bacteriological contamination in relation to well location above or below the marine limit, amount of superficial deposits, depth to bedrock in the well point, length of casing, top of casing situated above or below ground level and existence of well-house and/or concrete well-protection.

	Total number of wells	Bacteriological contamination (%)		
		None	HPC	Coliforms*
Well location above marine limit (a.m.l.)	20	30	25	45
Well location below marine limit (b.m.l.)	40	47	23	30
Medium to thick superficial deposits (category 1)	35	51.5	25.5	23
Thin or discontinues superficial deposits (category 2)	25	28	20	52
Well location a.m.l. with medium to thick superficial deposits	9	22	33	45
Well location a.m.l. with thin or discontinues superficial deposits	11	36.5	18	45.5
Well location b.m.l. with medium to thick superficial deposits	26	61.5	23	15.5
Well location b.m.l. with thin or discontinues superficial deposits	14	21.5	21.5	57
Depth to bedrock from surface in the well point > 10 m	6	66	17	17
Depth to bedrock from surface in the well point > 5 including 10 m	11	54.5	9	36.5
Depth to bedrock from surface in the well point > 0 including 5 m	19	31.5	26.5	42
Depth to bedrock from surface in the well point = 0 m	7	28.5	43	28.5
Length of well casing > 10 m	9	56	11	33
Length of well casing > 5 including 10 m	11	63.5	27.5	9
Length of well casing > 0 including 5 m	16	25	25	50
Length of well casing > 2.5 including 5 m	9	33	22	45
Length of well casing > 0 including 2.5 m	7	14	29	57
Top of well casing situated below ground level	19	31.5	31.5	37
Top of well casing situated above ground level	39	43.5	20.5	36
Well-house without concrete well-protection	16	43.5	25	31.5
Concrete well-protection, no well-house	28	28.5	25	46.5
Concrete well-protection, 6 in combination with well-cover	34	32	27	41

* Some wells also have too high HPC

those situated in category 1. This indicates that factors other than the superficial deposits affect the bacteriological quality as well.

The design and protection of the wells will also affect the bacteriological quality of the groundwater. Several of the wells examined are placed inside a concrete well-protection, a well-house or both. The bacteriological quality is known for 54 of these wells. A well-house without a concrete well-protection is constructed for 16 of the wells and 43.5 % of them have a satisfactory water quality. The corresponding number is 28.5 % for the 28 wells designed with only a concrete well-protection. Based on this data, a well-house appears more efficient than a concrete well-protection to prevent bacterial contamination. But, table 1 also shows that other factors affect the water quality as well, because, as many as 56.5% of the wells with a well-house have unsatisfactory water quality. The thickness of the superficial deposits at the well location determines the length of the well casing, and table 1 shows similar results for these two factors. Of the wells with casing lengths of >5 m, 56-63.5 % have no bacteriological contamination against 31 % for wells with casing lengths <5 m (Tab 1).

Out of 58 wells examined, 39 have the top of the casing above ground level and for the remaining 19 the top of the casing is below ground level. Fewer wells in the latter group are without bacterial contamination compared with the first group (tab.1). Improper design of the well casing combined with leaks in the concrete well-protection are most probably the main causes for bacteriological contamination of the groundwater in the wells. A closer examination of the 34 wells with only concrete well-protection or in combination with a well-cover, reveals that several of the concrete well-protections have leaks. Further, in many of these cases the well casing is cut below ground level. Due to the leaks, surface water can come inside the concrete well-protection and with the top of the casing below ground level, this water can then flow into the well. This also highlights the importance of multiple barriers for the protection of groundwater in a well from contamination derived from surface.

CONCLUSIONS

1 The bacteriological quality of groundwater in bedrock wells is dependent on several factors, including location, type of superficial deposit, well design and protection.
2 Bedrock wells located in areas with substantial thickness of superficial deposits are less prone to bacteriological contamination of the groundwater.
3 Well-houses appear to be more efficient in preventing bacteriological contamination compared with only a concrete well-protection.
4 Improper design and placement of the well casing may lead to contamination. The top of the casing should protrude above ground level to avoid inflow of surface water.
5 A groundwater well must be equipped with multiple barriers to ensure that the water will stay protected even though one of the barriers against contamination were to fail.

REFERENCES

Gaut S, Storrø G, Brattli B (2000) Bacterial contamination in Norwegian groundwater wells in bedrock. In: Sililo *et al.* (eds) Groundwater: Past Achievements and Future Challenges. Proc of the XXX IAH Congress on groundwater: Past Achievements and Future Challenges, Cape Town, South Africa, 26.now-1.dec. Balkema, Rotterdam, pp 751-754

Morland G (1997) Petrology, lithology, bedrock structures, glaciation and sea level: Important factors for groundwater yield and composition of Norwegian bedrock boreholes? Geological Survey of Norway report 97:122

Sosial- og helsedepartementet (1995) Forskrift om vannforsyning og drikkevann mm

From site characterization to performance assessment models for transport in a single fracture at Äspö site: assessment of retention processes

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A b s t r a c t : We propose here a procedure to build a Performance Assessment model for transfer in a single fracture case at the Äspö site (Sweden). This simplified model is based on a rather detailed knowledge as well as some tracer tests (non sorbing to medium sorbing) conducted in an identified structure. We focus here mainly on addressing the influence of matrix zones heterogeneity in the retention processes. We first describe the role played by the various types of immobile zones for the different regimes considered. Then, we build the simplified PA model, study the level of information provided by the tracer tests and other measurements, explicit the need for additional data requirements, and characterize the most important features as identified from sensitivity analysis.

PRESENTATION

We provide here with results obtained within the SKB Task Force. The objective of present Task6 is to build a bridge between site characterization (SC) models and performance assessment (PA) models on the basis of the Äspö underground laboratory dataset (Sweden) (refer to Selroos and Elert 2002). The first type of models are typically complex, incorporating detailed physical and geochemical properties and calibrated against short term and small scale in situ experiments. Performance assessment models are simpler, restrained to the main physical features, generally used to study a variety of possible configurations and apply to long time scales as well as larger spatial scales. The present part of the work deals with a single fracture case, (feature A, part of TRUE-1, Tracer Understanding Experiment, extension roughly 10m). We consider the transfer of several tracers (non sorbing to moderately sorbing) within this unit in different flow conditions (forced flow in pumping conditions and natural flow corresponding to post closure conditions). Refer to Fig.1.

We introduce here several models, from simple to more complex matrix zone geometries in agreement with the conceptual model of the fracture (Fig.2). These models (Fig.3, 4, 5) are calibrated against the experimental breakthrough curves for a series of non sorbing to moderately sorbing tracers. We study the regimes of these systems for slow velocity cases (typical of PA time scale post closure conditions for radial and uniform flow regimes) stressing the major features that have to be retained in building the prediction for PA time scale (Fig.3).

RESULTS

The role played by the different matrix zones for two flow regimes was studied for simple systems providing realistic matrix zone geometry (Model 1 & 2, Fig.3 & 4). These include gouge material, fracture coating, mylonite, altered and non altered diorite. Results show that for the quicker forced radial converging flow, only the higher diffusive zones in the vicinity of the fracture play a role (gouge material and fracture coating). For post closure flow regimes, all units are involved except fracture coating playing a minor role due to its reduced depth.

For low velocity regimes, the behaviour of the different matrix zones falls down into two main categories : (i) zones acting as classical matrix diffusion zones transitorily storing mass (altered and non altered Diorite); (ii) zones instantaneously invaded by the plume, following the kinetics of the fracture. The latter ones can be equivalently treated within a single continuum model considering an equivalent sorption coefficient Ka (gouge, fracture coating, mylonite). The PA model finally resulting for the whole system for post closure time scales is rather simple. It is similar to Model 1 (see Fig.3) and consists of an equivalent conducting zone (fracture with gouge material, fracture coating and mylonite considered by means of an equivalent surface sorption coefficient) and a matrix diffusion zone corresponding to altered and unaltered rock properties explicitly modelled.

Nevertheless, the real heterogeneity in the fracture system is badly constrained. The information available consists of measurements conducted on samples obtained from the boreholes, borehole imaging, measurements conducted on samples from geologically analogous zones as well as results from different hydraulic and tracer tests. One of the questions considered is relative to the level of information contained in the tracer tests conducted (Iodine and two moderately sorbing tracers, Strontium and Cobalt). Results show that :

- All 3 models considered (Model 1 to 3) allow for a good fit of the provided tracer test breakthrough curves (radial converging flow).
- The plume explores (i) the zones in the vicinity of the fracture and (ii) providing the larger diffusion coefficient values.
- The information contained in a breakthrough curve is an averaged value of the diffusion zones 'seen' by the plume.
- Considering the different flow regimes at stake (quick forced flow in pumping conditions vs. post closure slow flow conditions), the matrix zones explored by the tracer test behave as classical matrix zones for the quicker flow case but as immediate buffer for slow flow conditions as mentioned before. Considering the simple Model 1 geometry (Fig.2), one can show that, in the first case, they can be described by means of a first parameter group different from the one describing them in the second case. As a consequence, no information pertinent at post closure time scale can strictly be obtained from a tracer test conducted in another regime for the situation considered.
- Since these parameters are different combinations of matrix porosity, diffusion coefficient, fracture aperture and Kd, introducing a deterministic relationship between them (based on the measurements available) allows for identification of one single parameter. We addressed the question of identification of the diffusion coefficient field along the fracture with Model 3. We considered a Monte Carlo simulation approach to address this inverse problem issue, with trial and error procedure to fit the Iodine test. Results show that tracer tests badly constraint the system, some level of variance reduction is locally observed in the vicinity of the injection borehole where the contact times are the larger as a consequence of the radial structure of the flow.

These results are in line with conclusions from former studies considering the transport regimes (Ostensen 1998), parameter groups definition (Maloszewski and Zuber 1985), and equivalent properties (Carrera *et al.* 1998).

Sensitivity analysis to the different units of the system were conducted for post closure flow regimes. We observed a high sensitivity to the most diffusive zones parameters (porosity, diffusion coefficient and depth for gouge, fracture coating, mylonite) but low sensitivity for altered and non altered Diorite (porosity, diffusion coefficient, depth) although these latter zones could potentially provide the larger diffusion volumes if the contact time was to be sufficient.

MAJOR CONCLUSIONS AND PERSPECTIVES

The main results of this study follow.

- Tracer tests provide a very limited amount of information. One should rely upon direct measurements (possibly from geologically analogous zones).
- The matrix zones show two distinct behaviours for PA time scale. The resulting PA model is very simple.
- The retention effects are most related with high diffusion and porosity zones close to the mobile zones. Refined characterization of the former is required involving their statistical spatial structure.

We restrained here to simple flow paths (typically one channel). Future phases of the Task Force will involve a 200m fractured block and refined description of fractured zones.

REFERENCES

Selroos JO, Elert M (2001) TASK 6A and B modeling task specifications. Äspö Task Force, April 2001

Ostensen R (1998) Tracer tests and contaminant transport rates in dual porosity formations with application to the WIPP. Journal of Hydrology 204(1998):197-216

Maloszewski P, Zuber A (1985) On the theory of tracer experiments in fissured rocks with a porous matrix. Journal of Hydrology 79(1985):333-358

Carrera J, Sanchez Vila X, Benet I, Medina A, Galarza G, Guimera J (1998) On matrix diffusion : formulations, solution methods and qualitative effects. Hydrogeology Journal 6:178-190

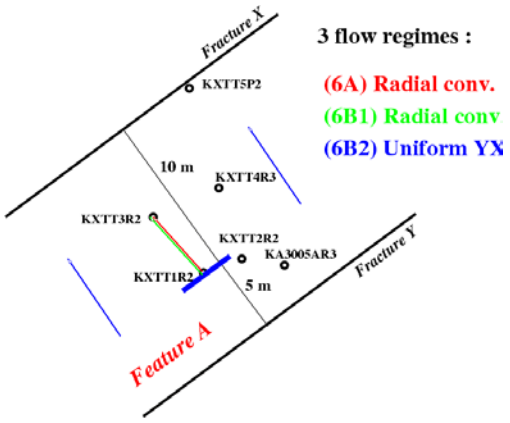

Figure 1. Flow regimes considered : quick (6A), slow (6B)

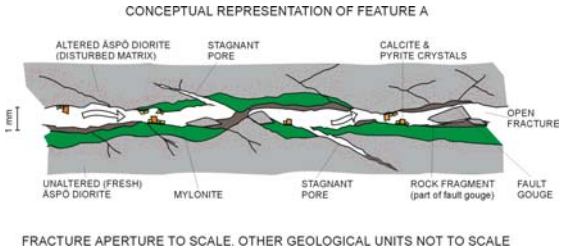

Figure 2. Conceptual model of the fractured zone

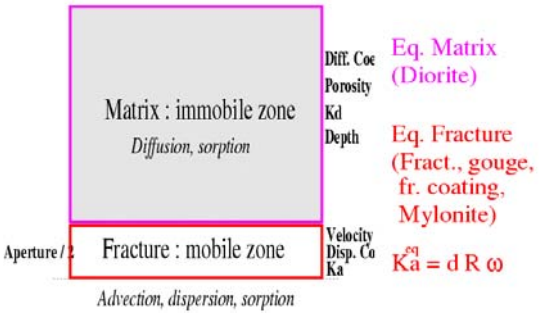

Figure 3. Model 1 and equivalent PA model

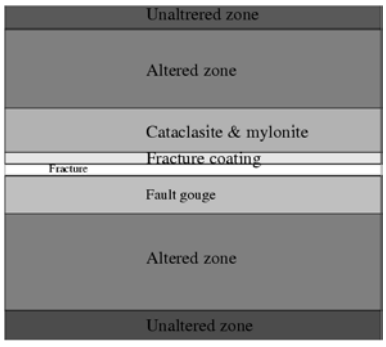

Figure 4. Model 2, deterministic heterogeneity

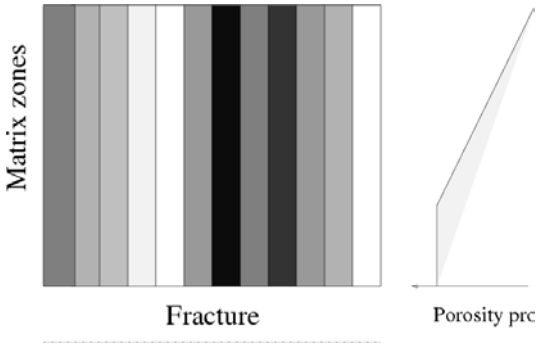

Figure 5. Model 3, stochastic heterogeneity

Anthropogenic influences on hard-rock hydrogeology: Linares granite mining district, Spain

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A b s t r a c t : Some of the results of the hydrogeological research carried out in the Linares mining district (Andalusia, South Spain) during the 2000-2002 period include: a) the evaluation of old mine voids, most of them flooded at present; b) the quantification of water resources and, particularly, the recharge of the batholith and its drainage by pumping and gravity; c) the hydrogeological regime of the groundwater flow systems based on piezometric controls, hydrochemical monitoring and well logging. The hydrogeological characteristic of the studied area are strongly influenced by anthropogenic effects which lead to consider them as quite anomalous in hard rock settings: infiltration coefficient of around 15%; pumping rates in deep open wells of 10-50 L/s; groundwater discharge by a drainage adit with flow peaks of more than 100 L/s; overall porosity of the mined fraction of the batholith of around 0,03%.

INTRODUCTION

The Linares batholith (extension: 80 km^2) is a small granitoid massif emplaced at the end of the Hercynian orogenic cycle. The major tectonic deformation in the last stages of this cycle produced a fracture network that conditioned the generation of ore veins, mainly galena (Azcárate 1977). The posthercynian subhorizontal cover is made up of Triassic lutites, Miocene marls and Quaternary alluviums. The relief of the area is gentle, with an average altitude of outcrops of around 500 m a.s.l. (fig.1). The area has a Mediterranean climate. The average annual precipitation is slightly less than 600 mm, with practically no rainfall from June to September.

Exploitation of the ores by underground mining is known since Roman times. The peak in Pb production was registered around the beginning of the XX century, when this district became the world´s first supplier, related to the implementation of efficient mine dewatering schemes. During the 50s the exploitations faced problems derived of pumping water from depths of more than 500 m. At the end of the 80s the last exploitations ceased. Then, an important volume of the workings became flooded after stopping the dewatering operation.

In the area there are at present some hydrogeologic features that can be considered anomalous in hard-rock settings which are thought to be the consequence of anthropogenic influences.

HYDROGEOLOGICAL SETTING

It is worth to note here the construction in the late 50's of an important drainage adit of 12 km long, and depth generally between 200-300 meters which crossed a significant number of mines, designed to minimize the pumping elevations (fig.1). It was originally designed to evacuate 600 L/s (Gutiérrez-Guzmán 1999). The abandonment of mining works led to the existence of a large volume of voids which are partially flooded at present due to the cease of dewatering. This drainage adit now acts as the main discharge point by gravity from the batholith.

Figure 1 sketches this drift (D1 portal) and the framework of connected flooded voids that normally reach depths of around 700 m, but with maximum values of more than 1000 m. Mines in the borders of the district are not connected to the drainage adit and piezometric levels are conditioned by the vicinity of the streams.

Growing requirements of groundwater resources for irrigation of new plantations of olive trees in the area –which is at present an economically profitable activity- have led to pump directly (up to around 50 L/s) from the abandoned shafts (fig.1).

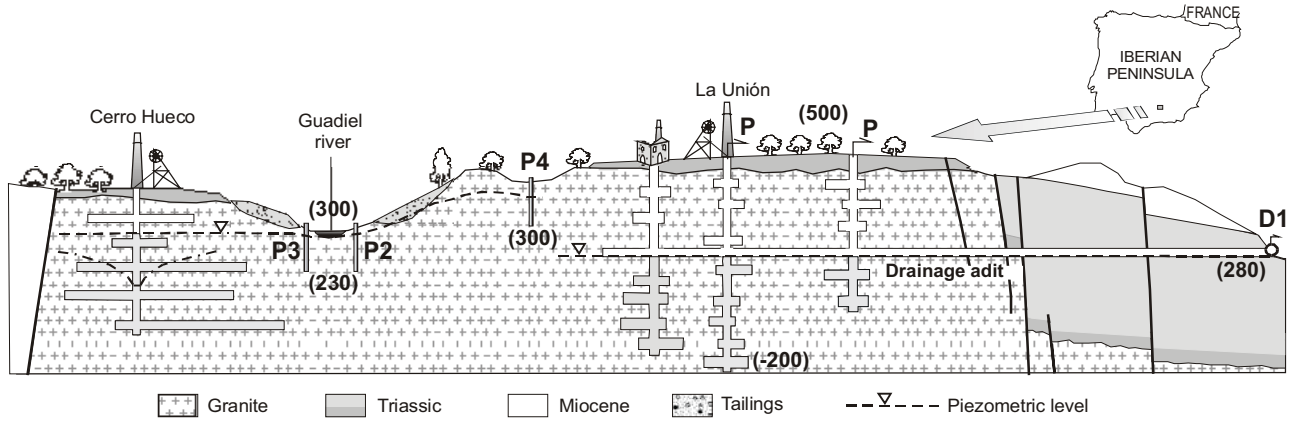

Figure 1. Sketched cross-section of the study area and location of the monitoring points: D1 portal; P2, P3 and P4 boreholes. Numbers between brackets indicate approximate altitudes. P: pumping in abandoned shafts

RESULTS

The evaluation of groundwater storage in mine voids has been based on digital image analysis of mine documents. The results indicate a volume of around 12 hm^3, approximately the 70 % of it being saturated. Nearly one third of this volume is above the level of the adit and assures the gravity discharge by this point.

The quantification of water resources in the study area has been made using a model of distribution of the effective precipitation over the area. The main recharge to the batholith comes from the precipitation over its outcrops, and amounts an average of 7-8 hm^3/a (Marín-Lechado 2002).

Most of the pumping from old mining shafts and from wells in sectors of weathered/fractured granite are currently used for irrigation purposes. The average volume exploited yearly is roughly similar to the above mentioned recharge. The discharge through the drainage adit has been estimated by means of seriated measures during the 2000-2002 period. Figure 2 shows the evolution of the registered values.

According to the water-balance estimations, the batholith is at present nearly in equilibrium conditions or maybe showing a slight trend towards the decrease in groundwater storage (Benavente *et al*. 2002).

The hydrogeological regime of the groundwater flow in sectors out of the influence of the adit can also be illustrated from the piezometric control in three monitoring boreholes: P2, P3 and P4 (fig.1 and 2).

The groundwater chemistry has been the object of previous researches: Hidalgo *et al*. (1999) and Hidalgo and Benavente (2001). The groundwater from the weathered/fractured granite (electrical conductivity of 400-600 µS/cm; HCO_3-Ca or Ca-Na type) can be separated of that from the mine shafts and drifts (1000-1600 µS/cm; SO_4-Ca type).

Well logging has been performed in the P2, P3 and P4 monitoring boreholes. In the three cases, there is a top layer (less than 10 m) of unconsolidated materials. The underlying granite appears mainly fissured (P4), or with alternating zones of compact and fissured nature. Slug tests carried out in these points give values of around 0.5 m/d in P4 and one order of magnitude less in the other two.

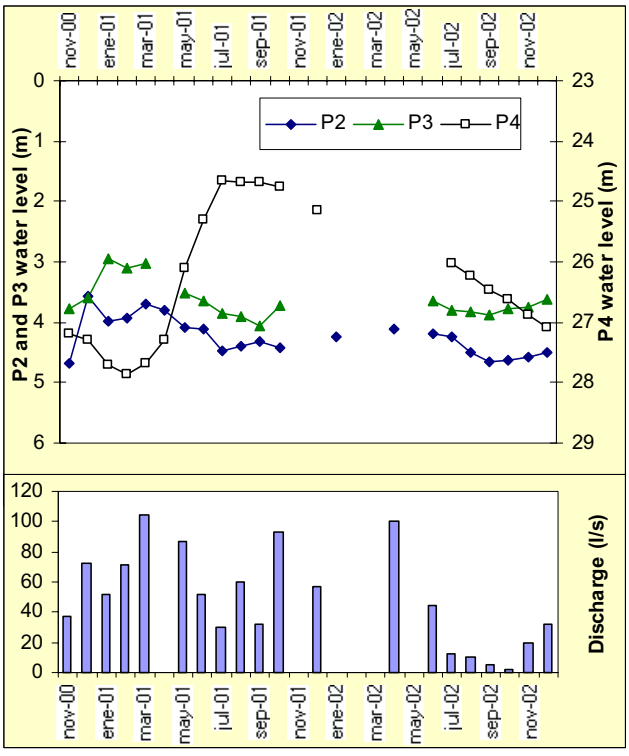

Figure 2. Piezometric control in the monitoring boreholes (P2, P3 and P4) and seriated measures of the discharge through the drainage adit (2000-2002 period)

Electrical conductivity logs show fairly constant values of around 550-650 µS/cm through the granite materials, but in the two points situated in the vicinity of the Guadiel river, less mineralized waters (300-500 µS/cm) occur in the first ten meters, due to mixing with fluxes in the top layer. Temperature logs indicate an average thermal gradient of 0.3ºC/100 m in P4, and five times greater in P2 and P3. Logging of flow –direction and magnitude- indicate downward values of 0.12-0.24 L/s in P4, and upward of 0.03-0.06 L/s in P2-P3.

CONCLUSIONS

The average discharge of the drainage adit is slightly less than 2 hm^3/a. The peak value during the recording period appears in the rainfall recharge season and exceeds 100 L/s. The lowest values are less than 10 L/s, measured at the end of the summer (fig.2). As a response of increased pumping from the connected shafts, the adit flow seems to follow a decreasing trend which can led to the complete exhaustion of this point in a few time.

The average infiltration coefficient over the batholith has been evaluated in 15%. The piezometric evolution in the boreholes shows different trends, caused by their topographical situation in recharge (P4) or discharge zones (with some mixing from surface formations: P2-P3). This is in agreement with the information provided by well logging.

The groundwater chemistry has been interpreted mainly as the result of sulphide oxidation. The water type of the main drainage adit is intermediate between the different sampled points, according to its hydrogeological nature.

The comparison of the mine voids quantification with the geometry of the mined fraction of igneous massif lead to an overall value of anthropogenically derived porosity of around 0.03%.

As a general conclusion, it can be stated that although the granite outcrops are considered in regional hydrogeological surveys as areas without interest for groundwater development, the situation in the Linares case is anomalous both for the volume of reserves generated and by the kind of present exploitation, that provides pumping rates of some tens of L/s. The present situation, however, can be no longer sustainable.

ACKNOWLEDGMENTS

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REFERENCES

Azcárate JE (1977) Mapa geológico y memoria explicativa de la hoja 905 (Linares), escala 1:50.000, Plan Magna. IGME, 35 pp

Benavente J, Hidalgo MC, Marín C, Rubio-Campos JC (2002) Groundwater resources development from abandoned mining works in granitic terranes (Linares district, Spain). In: Groundwater and Human Development, Proc XXXII I.A.H. Congress

Gutierrez-Guzmán F (1999) Las minas de Linares. Apuntes históricos. Colegio Oficial de Ingenieros Técnicos de Minas de Linares, 667 pp

Hidalgo MC, Benavente J, Rey J (1999) First results on the presence of metallic contaminants in waters after the abandonment of a sulphide mining district (Linares, Spain). In: *Mine, Water & Environment*, Proc IMWA Congress

Hidalgo MC, Benavente J (2001) Controls on groundwater chemistry in the Linares lead-copper abandoned mines (Spain). In: Seiler K-P, Wohnlich S (eds) New approaches characterizing groundwater flow , Vol 2, Balkema, 1199-1202

Marín-Lechado C (2002) Geometría y estimación de huecos mineros en el batolito de Linares (Jaén). Implicaciones hidrogeológicas Dissert, University of Granada, Spain

Bacteria transmission in fissured carbonates: fatal consequences in Walkerton, Ontario

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Abstract: In the spring of 2000, 2300 residents of Walkerton, Ontario became seriously ill and seven people died due to contaminated well water. The Ontario government responded to the tragedy with an independent "Commission of Inquiry"; the inquiry report was published during 2002. Part 1 of the report confirmed that the outbreak was caused by *Escherichia coli (E. coli*), and *campylobacter* in the well water; *E. coli* O157:H7 was the primary cause of the deaths. DNA analysis revealed cattle manure as the bacterial source, and fissure flow in the Palaeozoic carbonate aquifer was found to have played a critical role. In Part 2 of the Commissioner's report, 17 of 93 recommendations for improving Ontario's water delivery system related to groundwater source protection e.g. decommissioning of abandoned wells, wellhead design, and watershed-based source protection plans. Work is now underway to implement these recommendations and develop protection strategies that are appropriate to the hydrogeological conditions encountered.

BACKGROUND

In the spring of 2000, residents of Walkerton, Ontario (Fig.1) experienced a tragedy that should never have happened. It began on May 18th, when a number of children failed to attend school due to illness. Two of these students were admitted to the local hospital with severe diarrhoea and abdominal pains. Food poisoning, possibly due to undercooked ground beef (CDCP 1993) was immediately suspected as the cause. Initially, very little action was taken.

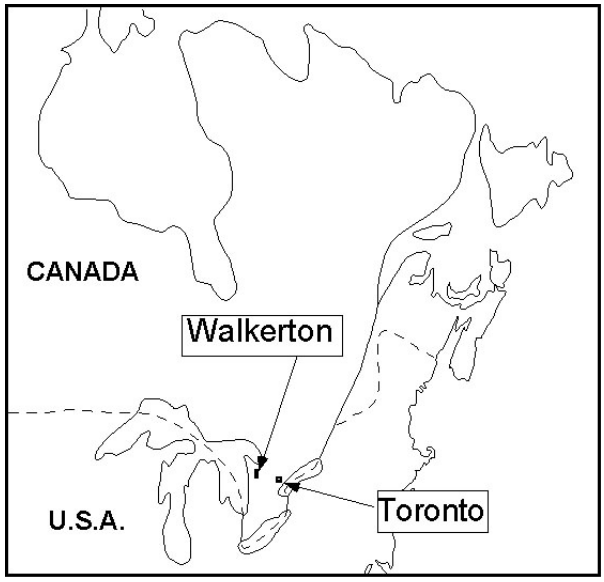

Figure 1. Walkerton is located above the Niagara Escarpment, about 200 km west of Toronto

Over the next several days, sickness spread quickly in the community. The Walkerton hospital was inundated with telephone calls and with people visiting the emergency clinic. One person died on May 22nd and by May 24th, three others had suffered the same fate. Eventually, by the time the outbreak was brought under control, 2300 people had become ill (almost half the town's population) and seven people died (Howard 2001). Some suffered ailments that would affect them for the rest of their lives.

Despite the rapidity by which the sickness spread, the ultimate cause of the tragedy – contaminated well water from one or more of the town's wells, was not reliably determined until May 21st, three days after the problems began. A boil-water alert was immediately issued but the warning had clearly come too late. Comprehensive hydrogeological investigations began immediately and included both pumping and tracer tests involving all suspected wells (Golder Associates Ltd. 2000; OMOE 2000a).

THE INQUIRY

In response to the tragedy, the Provincial government set up an independent "Commission of Inquiry" under Justice Dennis O'Connor. Starting in July 2000, and lasting 9 months, the hearing heard from 114 witnesses including two former Ministers of the Environment, and the Premier of Ontario. The report was issued in two parts. Part 1 (O'Connor 2002a) was published in January 2002 and focused on the cause of the outbreak at the local level. Part 2 (O'Connor 2002b) followed three months later and examined, more broadly, the water delivery system across the whole Province of Ontario.

THE FINDINGS

Part 1

It is now clear that the outbreak in Walkerton was caused by *Escherichia coli (E. coli*), and *campylobacter* in groundwater obtained from Well #5 (Figs 2 and 3). In particular, *E. coli* O157:H7 was determined to be the primary cause of the deaths. Although most strains of E. coli are harmless and live naturally in the intestines of healthy humans and animals, E. coli O157:H7 can produce a powerful toxin that can cause severe illness including liver failure (Boyce *et al*. 1995, Mead and Griffin 1998, Slutsker *et al.* 1997).

DNA analysis conducted at the site demonstrated that cattle manure was the source of the bacteria. The manure was applied to Lot 19 in April, 2000, about 80m from Well #5 (Fig.3). The bacteria appear to have been mobilized by unusually heavy rainfall. 138 mm of rain (approximately 20% of the normal annual amount) fell between May 1st and May 12th, 2000.

Less conclusively determined was the exact mechanism by which the bacteria reached and entered the well. The landscape around Walkerton is glaciated and best described as gently rolling hills etched into Palaeozoic carbonates. These carbonates are semi-karstic and form the major aquifer. They are draped by a thin veneer of till (a "stony, sandy silt to silt till") known as the Elma Till.

Hydrogeological investigations confirmed that shallow fissure flow in the carbonate aquifer was extremely important in promoting the rapid transmission of the bacteria. Well #5 was just 15m deep and all water from the affected well entered via a single zone of fissuring between 5 and 7m below ground surface. More

speculative is the means by which water from the agricultural field managed to penetrate the glacial till overburden. There is one suggestion that fence-post holes may have allowed runoff water to penetrate the till fairly rapidly, at least to shallow levels. However, permeable zones within the till must undoubtedly have contributed to transmission of the contaminated water. Two findings in Part 1 of the Commissioner's Report were particularly significant:

- the owner of the farm had employed proper industry practices for spreading the manure and should not be faulted.
- the outbreak would have been prevented if continuous chlorine residual and turbidity monitors had been installed in the contaminated well.

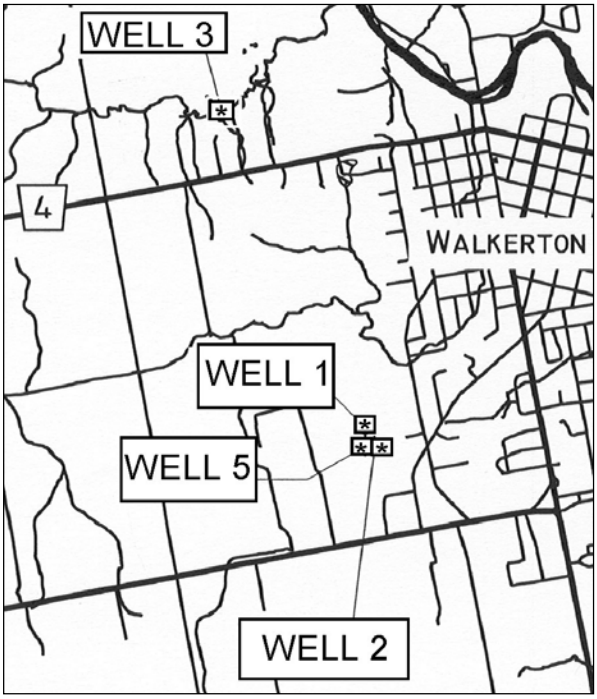

Figure 2 The town of Walkerton showing the location of Well #5

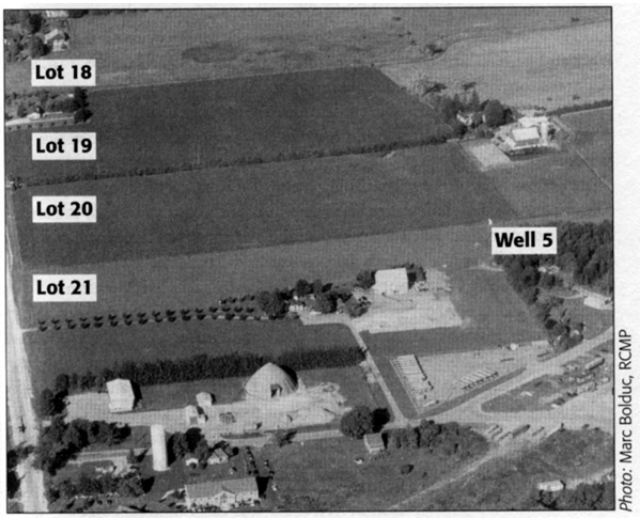

Figure 3. Aerial view showing the relative locations of Lot 19 and Well #5

Part 2

Part 2 of the Commissioner's report was published in 2002 and identified numerous shortcomings in Ontario's water delivery system including, but by no means limited to, the Province's water supply regulations and compliance measures (see for example OMOE 2000b and 2000c). The report listed 93 recommendations for improvement, including 17 recommendations that related specifically to groundwater source protection issues such as:

- decommissioning of abandoned wells,
- wellhead design, and
- watershed-based source protection plans.

The Commissioner went so far as to recommend that watershed-based source protection plans be developed for all watersheds in Ontario, and that as a minimum requirement these plans should be based on groundwater flow system models that can predict the fate of all pollutants in the watershed. Such sweeping recommendations promise to radically alter the Province's groundwater industry. Major work is now underway to implement the recommendations and develop protection strategies that are appropriate to the hydrogeological conditions encountered.

REFERENCES

Boyce TG, Pemberton AG, Wells JG, Griffin PM (1995) Screening for Escherichia coli O157:H7 - a nationwide survey of clinical laboratories. J Clin Microbiol 33:3275-3277

Center for Disease Control and Prevention (CDCP) (1993) Update: multistate outbreak of Escherichia coli O157:H7 infections from hamburgers--western United States, 1992-1993. Morbidity and Mortality Weekly Report (MMWR) 42:258-63

Evers S, Lerner DN (1998) How uncertain is our estimate of a wellhead protection zone? Ground Water 36:49-57

Golder Associates Ltd. (2000) Hydrogeological Assessment of Bacteriological Impacts on Walkerton Town Wells, Municipality of Brockton, County of Bruce, Ontario. September, 2000, 001-3105-1, 50pp

Howard KWF (2001) Polluted groundwater - deadly lessons from Walkerton, Ontario, Canada Proceedings of the XXXI Congress of the International Association of Hydrogeologists. Munich, Germany. September 2001 4pp

Mead PS, Griffin PM (1998) Escherichia coli O157:H7. Lancet 352:1207-12

O'Connor, DR (2000a) Report of the Walkerton Inquiry - Part 1 - The events of May 2000 and related issues. Queens Printer for Ontario. 504 pp

O'Connor DR (2000b) Report of the Walkerton Inquiry - Part 2 - A strategy for safe drinking water. Queens Printer for Ontario. 588pp

Ontario Ministry of the Environment (OMOE) (2000a) Technical Report on the Status of the Walkerton Water Supply System, Volume 1, Technical Report. November 2000. PIBS 4000E-01; ISBN 0-7794-0405-X 50 pp

Ontario Ministry of the Environment (OMOE) (2000b) Protecting Drinking Water for Small Waterworks in Ontario - A Discussion Paper. PIBS 4070e. ISBN 0-7794-0042-9, 7pp

Ontario Ministry of the Environment (OMOE) (2000c) Drinking Water Protection - regulation made under the Ontario Water Resources Act Ont Regulation 459/00 August 8 2000. Reg 2000.0348.e 28 pp

Slutsker L, Ries AA, Greene KD (1997) Escherichia coli O157:H7 diarrhoea in the United States: clinical and epidemiologic features. Ann Intern Med 126:505-13

Groundwater acidification in Central Europe: progress, regress or stable state?

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A b s t r a c t : The attenuation of heavy industry and desulphurization of power plants burning lignite resulted in the Central Europe in the reduction of total atmospheric deposition of sulphur. On the other hand, the increase in total nitrogen deposition on regional scale takes place even in areas, which were considered to have not been affected by anthropogenic activities. The established trends in the acid atmospheric deposition and its impact on groundwater quality will become evident with some delay. A high runoff of sulphates still occurs at the present time and will last in future in regions, which were exposed to acid precipitation for a long time.

INTRODUCTION

The Czech Republic belongs from the viewpoint of acidification among the most affected regions of Europe. The area of the so-called "Black triangle" at the boundary of Germany, Poland and Czech Republic (Fig.1) was towards the end of the last century one of the major producers of acid atmospheric deposition world wide. The peak of highest intensity of acid atmospheric deposition was recorded in 1980. By that time the total deposition of sulphur fluctuated around 108 kg per hectare per year (Černý and Pačes 1995).

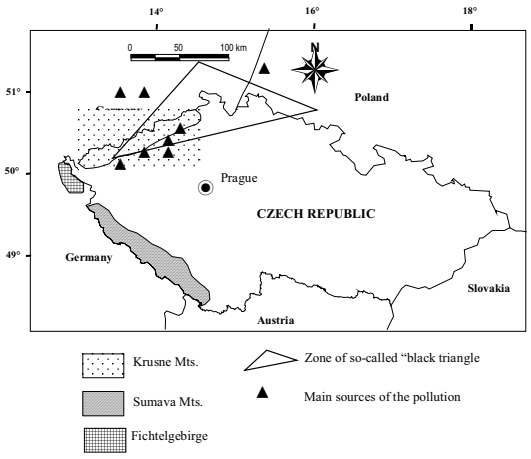

Figure 1. Situation of test regions

The process of acidification has had a considerable impact on the quality of local groundwaters. The alkalinity dropped considerably when compared with results of chemical analyses from the fifties of the last century. The HCO_3 locally completely disappeared in apical parts of the mountain range. On the other hand, the concentrations of nitrates and sulphates increased (Hrkal 1992). Average nitrates concentration of 0.06 meq/L in the period 1955-69 increased to 0.31 meq/L in the period 1980 – 90. With the exception of high altitude zone of the Krušné hory (Mts.), where removal of forest cover reduced the proportion of dry deposition, the average sulphates concentration increased from 1.2 meq/L in the period 1955-69 to 1.5 meq/L in 1980-90.

Nevertheless, there exist within the territory of the Czech Republic some areas, which are considered to be still unspoiled by acidification. If the Krušné hory Mts. should serve as a region affected by extreme acidification, the Šumava has been long time considered as one of the least affected regions in central Europe. It is obviously due to absence of such sources of pollution like power plants, heavy or chemical industry in close neighbourhood of the Šumava region.

Political and particularly economical changes in Central Europe strongly influenced the quality of the environment. Large-scale desulphurisation programs together with attenuation of main sources of the pollution – heavy and chemical industry resulted in the reduction of total atmospheric deposition. Well, is the problem of the acidification finally solved? The answer to this question has been one of the main tasks of 5th Framework programme project LOWRGREP.

TRENDS OF ATMOSPHERIC DEPOSITION

Intense investigation of acidification of surface and groundwaters began in the Czech republic in the second half of the eighties by the establishment of a grid of small experimental catchments GEOMON coordinated by the Czech Geological Survey. Based on GEOMON long term series data (Fottová 2002) and information from the German pilot area a trends of total sulphur and nitrate atmospheric deposition has been assessed. GIS methodology, taking into account the morphological and climatological parameters and information about the vegetation cover, allowed the extrapolation of point data from experimental catchments to the regional scale. The resulting map expresses separately the deposition of sulphur and total nitrogen in mol/ha/km^2.

It seems that large investments directed in implementation of the so-called desulphurization projects turned out to have been very successful. As demonstrated on the results achieved during the execution of the LOWRGREP project, the lower concentrations of sulphur in acid atmospheric deposition show prolonged trends. This general tendency is documented in Fig.2 showing the situation in the Jezeří catchment in the Krušné hory area. Similar trend was observed in Šumava, and in Fichtelgebirge in Germany (Matzner *et al.* 2001).

However, the optimistic conclusions showing the decline in sulphur deposition, are corrected or even eliminated by a new problem. While sulphur not long ago played the major role in acid atmospheric deposition, its role is nowadays taken over by nitrogen. All tested localities showed increased concentrations of nitrogen in atmospheric deposition, i.e., in the form of ammonia as well as in form of nitrates. This increase is obviously due to progressing intensity of motor traffic.

This new trend should be clearly demonstrated on the comparison of two, seemingly different regions – Krušné hory and Šumava. While the average total deposition of sulphur in Šumava has been equal to 339 mol/ha/year in 1994, its concentration in the Krušné hory region is threefold higher being 1019 mol/ha/year. The difference in total nitrogen deposition in both regions is much lower. The mean total deposition of nitrogen in Šumava was equal to 605 mol/ha/year in 1994, whereas in the Krušné hory region was only twice as much (1324 mol/ha/year). Characteristic feature in the Krušné hory area is markedly higher values of total deposition in its south-western part. However, if we compare data from north-eastern part of the Krušné hory region with those obtained in Šumava, then we obtain similar values of total nitrogen deposition!

Assessment of groundwater quality was based on the LOWRGREP project regional monitoring network data. Chemical analyses from 65 springs monitored in the Šumava region and 32 springs in the Krušné hory in monthly intervals

were taken into account. Consequently, a database consisting of a total of 2,320 analyses of spring water was made available. These data has been compared with old groundwater quality unsystematic monitored between 1955 - 1990.

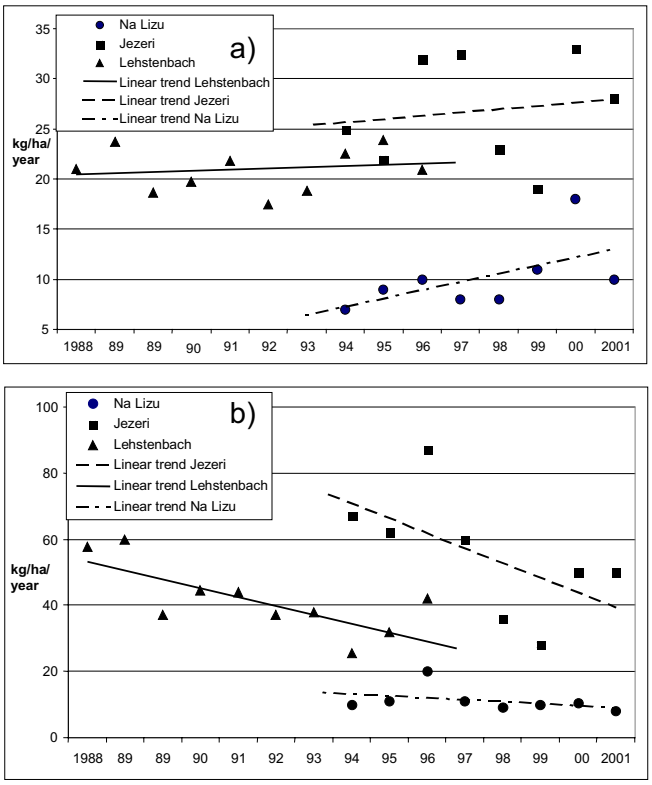

Figure 2. Comparison of sulphur (a) and nitrogen (b) throughfall changes in Krušné hory (Jezeří catchment), Šumava (Na Lizu catchment) - data from Fottová 2002 and Fichtelgebirge (Lehstenbach catchment) - data from Matzner *et al.* 2001)

TRENDS OF GROUNDWATER QUALITY

As follows from the comparison of groundwater chemistry in both regions in spite of decline of sulphur deposition, high concentration of SO_4^{2-} is still dominant in Krušné hory. The rock massif such as the Krušné hory gneisses, which is more resistant against acidification, can for longer period of time protect groundwaters against impacts of acid rains. On the other hand, after disappearance or reduction of impacts of acid deposition, it may take a long time to restore the original conditions, and the rock massif may alternatively either to maintain or support the acidification. Groundwater acidification in such aquifers will not be easily reversed by decreasing SO_4^{2-} deposition because of the release of previously stored SO_4^{2-}.

The negative role of the SO_4^{2-} storage in the weathered substrata has been proved also in the German experimental catchment of Lehstenbach in Northern Bavaria (Manderscheid *et al.* 2000, Lischeid *et al.* 2000.).

The direct impact of acid atmospheric deposition in regional point of view can be demonstrated in both of the regions on the contents of nitrates and sulphates. The natural background value of sulphates in Proterozoic metamorphic rocks ranges between 10 – 20 mg/L. This category in the Šumava region represents almost 90% of all monitored springs. However, only 25 % springs in the Krušné hory area fall into this category of natural background. This is obviously due to the increased runoff of sulphates.

Similar although not as striking is the situation in the case of nitrogen. Nitrates in groundwaters in regions with no farming activities should occur only in traces. The value of 5 mg/L, which is the highest concentration of nitrates in areas with no pollution (*Rosendorf et al.* 2003), is in the Šumava and Krušné hory regions exceeded in 25 and 60 % of springs, respectively.

CONCLUSION

- The issue of acidification of surface and groundwaters in Central Europe remains still relevant and contemporary problem to be resolved,
- The dominant role of sulphur in acid atmospheric deposition has been gradually taken over by nitrogen, mostly on regional scale. The attenuation of heavy industry and desulfurization of power plants brings positive results. However, more intense motor traffic is responsible for increase of nitrogen emissions,
- Come-back to original groundwater quality should be a very long process

ACKNOWLEDGMENTS

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REFERENCES

Černý J, T Pačes (1995) Acidification in the Black Triangle Region. 5th International Conference on Acidic Deposition, Science and Policy, Prague

Fottová D (2002) Assessment of mass flux in the small catchment network GEOMON in Czech republic. MS Annual report. Czech Geological Survey. Prague

Hrkal Z (1992) Acidification of groundwater in the Bohemian Massif Nor geol unders Bull no 422:97-102

Lischeid G, Moritz K, Bittersohl J, Alewell Ch, Matzner E (2000) Sinks of anthropogenic nitrogen and sulphate in the Lehstenbach catchment (Fichtel gebirge) Lessons learnt concerning reversibility. Silva Gabreta 4:41-50 Vimperk

Manderscheid B, Schweisser T, Lischeid G, Alewell C, Matzner E (2000) Sulfate pools in the weathered substrata of a forested catchment. Soil Scientific Society American Journal 64:1078-1082

Matzner E, Alewell C, Bittersohl J, Lischeid G, Kammerer G, Manderscheid B, Matschonat G, Moritz K, Tenhunen JD, Totsche K (2001) Biogeochemistry of Spruce Forest Catchment of Fichtelgebirge in Response to Changing Atmosperic Deposition. Ecologicasl Studies 147 JD. Tenhunen *et al*. (eds) Ecosystem Approaches to Landscape Management in Central Europe. Springer-Verlag Berlin 2001

Rosendorf P (2003) Limitation of regional pollution of surface and groundwaters in Czech Republic (In Czech) – Final report. VÚV TGM. Praha

Hydrogeology and hydrochemistry of the Triassic rocks of the Sydney basin

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A b s t r a c t : Groundwater in the Triassic rocks of the Sydney Basin, in southeastern Australia, is a useful resource for small-scale water supplies, and supports valuable ecosystems. The hydrogeology and hydrochemistry of the sandstone aquifers within the basin are quite complex, and present technical challenges during the construction of urban infrastructure. Numerical modelling of groundwater inflow and hydrochemical speciation modelling have been used to assess the impact of groundwater on tunnel construction.

INTRODUCTION

The central part of the Sydney Basin, in South-Eastern Australia, is dominated by rocks of Triassic Age. These rocks include the Wianamatta Shales, which occur beneath the Cumberland Plains to the west of Sydney, and the stratigraphically underlying Hawkesbury and Narrabeen sandstones, which are exposed in the cliffs around Sydney Harbour, along the adjacent coasts, and on the elevated plateaux of the Southern Highlands, Blue Mountains and Hawkesbury, where they are locally capped by remnants of Tertiary-age plateau basalts, and are confined beneath the Wianamatta Shales in the central part of the basin.

The Triassic sandstones and shales form a complex hydrogeological environment that is interesting and economically important from a number of perspectives. In the plateau areas, boreholes completed in the Hawkesbury Sandstone can provide moderate yields of potable-quality groundwater for both domestic and agricultural use. Indeed, production of bottled mineral water from sandstone aquifers has become a growth industry in these areas. Groundwater seeping from both Hawkesbury and Narrabeen sandstones is important in maintaining unique highland ecosystems known as hanging swamps, and in providing baseflow to local streams. There is sometimes conflict between these resource values and other economic activities such as quarrying of sandstone and basalt. Within the central part of the basin, groundwater has less economic and environmental value but can be a significant problem during development of transport infrastructure, particularly tunnels bored through the sandstones. It is also a potential vector of chemical contamination derived from industry.

This paper discusses the inter-relationship between hydrogeology and hydrochemistry in the sandstones and shales of the Sydney Basin, and is based on data derived from a wide range of groundwater resource, infrastructure development and contaminated land studies.

HYDRAULIC CHARACTERISTICS

Around Sydney, the hydraulic conductivity of the rock substance (the matrix or intergranular permeability) of the Hawkesbury Sandstone is generally low. This is because, in most sandstone units, the pore space is occluded by an intergranular cement that may include clay minerals, silica, iron oxides and iron carbonates. There are exceptions, and relatively rare coarse-grained units, both massive and coarsely cross-bedded, may have significant intergranular permeability. Generally, however, groundwater flow occurs almost entirely through secondary features such as joints, bedding plane shears and other open.fractures. The dip of the bedding within the sandstone throughout the basin is typically very shallow, of the order of 1 or 2 degrees. A conventional model of groundwater flow in the Hawkesbury Sandstone is of a network in which high-angle joints connect bedding plane shears and some open low-angle joints. Groundwater flows along bedding planes until it encounters a vertical joint, then moves down to the next bedding plane.

For this reason, coupled with the near-horizontal bedding of the sandstone and the presence of some nearly impermeable beds – shales, ironstone lamination and very tight sandstone layers – permeability in the sandstone is highly anisotropic. Vertical hydraulic conductivity is much lower than lateral hydraulic conductivity.

In the Wianamatta Shales, primary permeability is very low, but secondary permaebility associated with fracturing can be locally significant.

The conventional concept of a water-table or phreatic surface below which the pore space and all fractures are saturated with groundwater does not correspond well with observations - particularly in deeply incised terrain – that closely spaced boreholes may show widely different and quite erratic groundwater levels. The rock substance may have such low permeability that fractures, or fracture systems, are effectively isolated, and have water levels that show only a very general regional pattern.

Throughout the Sydney basin, open, sub-horizontal fractures that can deliver very high water flows may be encountered in boreholes and excavations. These features generally occur below valley floors, and appear to be stress-relief fractures.

HYDROCHEMISTRY

Groundwater chemistry in the Hawkesbury Sandstone varies over a wide range. End-members of this range can be described as follows:

Type I — Low Salinity (TDS) calcium/sodium bicarbonate waters, low pH (down to 4) generally up to 10mg/L dissolved iron. Oxidising to moderately reducing.

Typical of outcrop areas with active groundwater circulation, e.g. the Blue Mountains, at elevations above or not far below discharge base level.

Type II — High salinity (TDS) sodium chloride waters. Neutral pH, very high dissolved iron and manganese. Highly reducing – Eh typically around the sulphate reduction level. May have significant hydrogen sulphide.

Typical of confined conditions (beneath Wianamatta Shales) and (in the central part of the basin) depths below discharge base where conditions are stagnant and there is almost no groundwater flow.

Groundwater within the shales is typically brackish or saline, and similar in composition to Type II sandstone groundwater.

The composition of these water types is illustrated in fig.1.

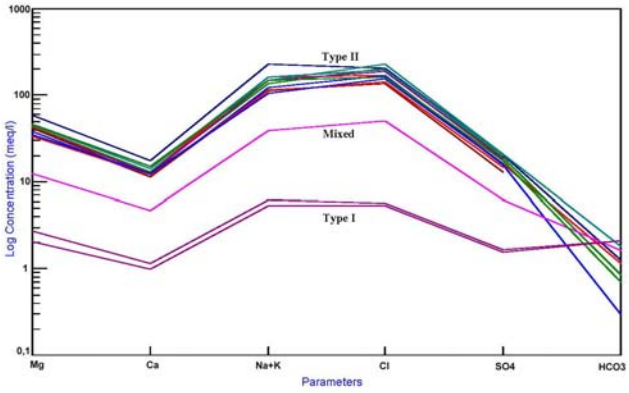

Figure 1. Schoeller diagram – main water types

GROUNDWATER RESOURCES

Aquifers within the Hawkesbury sandstone can typically provide yields to single boreholes that are in the range 0.5 to 1.0 litres per second (L/s). Where down-hole investigations have been carried out, it has been established that inflow generally originates from fractures.

Type I groundwater is exploited for small domestic supplies which are frequently used for garden irrigation rather than potable purposes, but also provides water for livestock. The increasing popularity of bottled "mineral" water has seen the development of numerous small-scale industrial abstractions, particularly in the Hawkesbury area to the north of Sydney.

Locally within the sandstone sequence (for examples, around Bowral in the southern highlands, areas of weakly cemented medium-coarse sandstones with significant inter-granular permeability occur. Average yields are higher in these areas, 2 to 3 L/s being common, with occasional higher yields. These areas have concentrations of groundwater abstraction.

Sydney's water supply is provided by a number of surface water systems, with one large dam in the southern Blue Mountains providing over 80% of the total supply. The strategic advantages of a more diversified supply are now recognised, and studies are in progress to assess the viability of a range of smaller scale supplies, including abstraction from the Hawkesbury Sandstone.

GROUNDWATER_DEPENDENT ECOSYSTEMS

In NSW the State Government has recognised the importance of ecosystems that are maintained by groundwater flows, and has issued a "groundwater dependent ecosystems policy" to help ensure the preservation of such ecosystems. The principal types of groundwater dependent ecosystems in NSW are coastal wetlands and hanging swamps; the latter are most significant with regard to the Hawkesbury Sandstone.

Hanging swamps occur at high levels on the steep hillsides and clifflines of the Southern Highlands, Hawkesbury and, particularly, the Blue Mountains. They are wetland ecosystems in areas otherwise dominated by dry eucalypt vegetation. They most commonly occur where vertical groundwater flow through the sandstone is restrained by claystone interbeds, a circumstance, which may also allow the formation of more cohesive and fertile soils. Sometimes, they are associated with horizontal groundwater flow along bedding plane shears.

Groundwater abstraction up-gradient from hanging swamps, reduction of groundwater recharge by pavement, sandstone extraction or drainage work, and groundwater contamination can all adversely affect these ecosystems; the potential for such effects is now taken into account in the planning process.

CIVIL ENGINEERING

Like many major cities, Sydney has a complex network of under-ground infrastructure. This includes an urban railway system, constructed progressively over the past 100 years, and a number of more recent additions including the Sydney Harbour Tunnel (1990), the Airport Railway (1998), Eastern Distributor Motorway (1999), M5 East Motorway (2000), Northside Storage Tunnel (2001) and Energy Australia Tunnel (2003). Currently two major projects, the Cross-City Road Tunnel and the Chatswood-Parramatta Rail Link are under construction.

The sandstone tunnels have been designed and constructed as fully drained tunnels. Traditionally, groundwater inflow had not been considered a serious problem, but tight specifications for recent projects (groundwater inflow limited to 1 L/s per km) and major groundwater-related problems with a new tunnel in Melbourne have resulted in a new focus on groundwater issues for current projects.

Numerical modelling has been used at the design stage to predict inflows into the newer tunnels. AQUIFEM I, MODFLOW and SEEP/W have been used, as well as a number of analytical methods. Although a reasonable number of permeability measurements are available from packer tests conducted in geotechnical investigation boreholes, it has been found that use of measured permeability values greatly over-predicts groundwater inflow. The approach adopted has therefore been to back-calculate permeability values from measured inflows to previous tunnel projects, and use these values in modelling inflow to new tunnels. The packer test permeabilities are used only as a guide to the local inflows that might be expected during construction. The presence of joint swarms, faulting and deep weathering beneath incised valleys can result in high local inflows. High inflows have also been experienced from fracturing associated with the Great Sydney Dyke.

Inflow of Type II or mixed groundwater to tunnels can pose problems that are potentially difficult and expensive to treat. The high salinity, low pH and high dissolved carbon dioxide of the water make it extremely aggressive to carbon steel reinforcement. It will slowly dissolve concrete and may cause sulphate stress-corrosion (SSC) cracking in some types of stainless steel. Precipitation of dissolved iron and manganese following gas exchange with the atmosphere leads to staining of internal surfaces and blockage of drainage systems. The water also requires treatment before it can be discharged to stormwater or sewer systems. PHREEQC has been used to study the speciation of dissolved components in this water.

The proliferation of drained underground infrastructure in central Sydney will result in long-term lowering of the water table in the sandstone beneath the city. Subsidence is not generally an issue in the high strength sandstones, but has to be considered where these are overlain by weathered, low strength sandstone or by superficial deposits that were previously saturated. It is possible that the lower discharge base will result in mobilisation of Type II groundwater from previously stagnant areas (already observed in one area), and feasible that seawater will be drawn into aquifers that previously contained fresh groundwater.

Multi-technological groundwater remediation in fractured rocks

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A b s t r a c t : The remediation activities were carried out at the site contaminated by TPH and BTEX. Due to the complexity of the hydrogeological conditions (presence of permeable zone with an intergranular porosity in the vicinity of the groundwater table and further the net of not interconnected fissures) the multi-technological approach for the remediation was necessary to reach the cleanup-limits. The remediation system involved pump & treat, bioventing, air-sparging, and enhanced biodegradation. The remediation was successfully terminated after 18 months.

INTRODUCTION

The remediation activities were carried out at the site in the southern part of the Czech Republic. The source of the contamination is the former petrol station, which was decommissioned some 25 years ago. The petrol station comprised a kiosk with the petrol pump and the underground tanks at the area of approx. 15 x 15 m.

The following clean-up limits were proposed for the remediation at the site.

Table 1. Clean-up limits

Compounds	Clean-up limit
TPH	2 500 µg.L^{-1}
Benzene	200 µg.L^{-1}
Σ BTEX	700 µg.L^{-1}

GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

From the geological point of view the site is situated on a belt of Susice – Votice complex of Moldanubian represented by paragneisses that are deeply weathered along the net of diverse fissures. Quaternary sediments consist of a deluvial soil and sandy-clayey eluvium to the depth of 1 – 2 m.

The depth to groundwater is approx. of 3.5 m. Hydraulic conductivity of this shallow unconfined fractured aquifer varies between 1.10^{-8} to 1.10^{-3} m/s.

The well-logging was utilized for the characterization of the hydrogeological conditions. The measurements indicated the presence of not interconnected fissures (except the permeable zone in the vicinity of the groundwater table level which probably refers to intergranular porous zone).

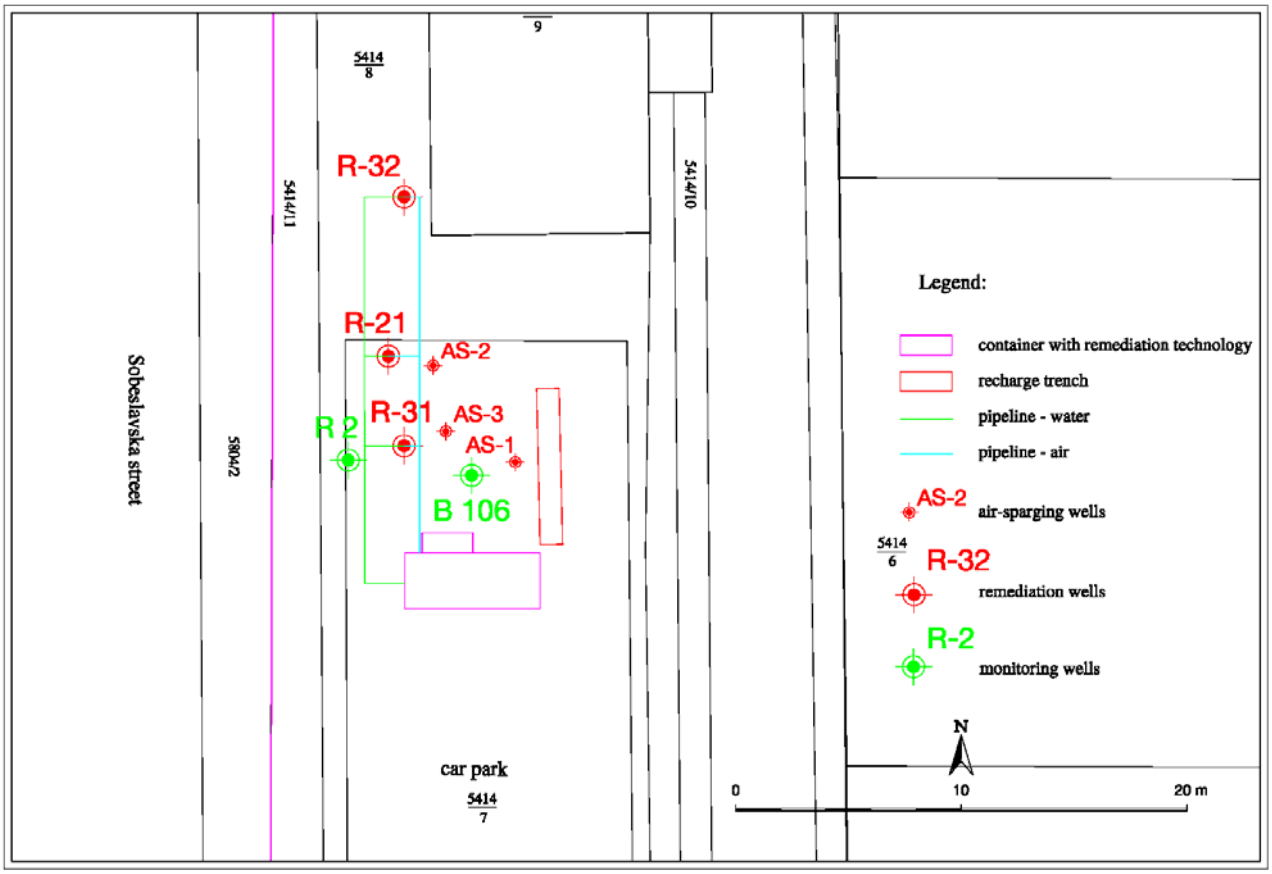

Figure 1. Site layout

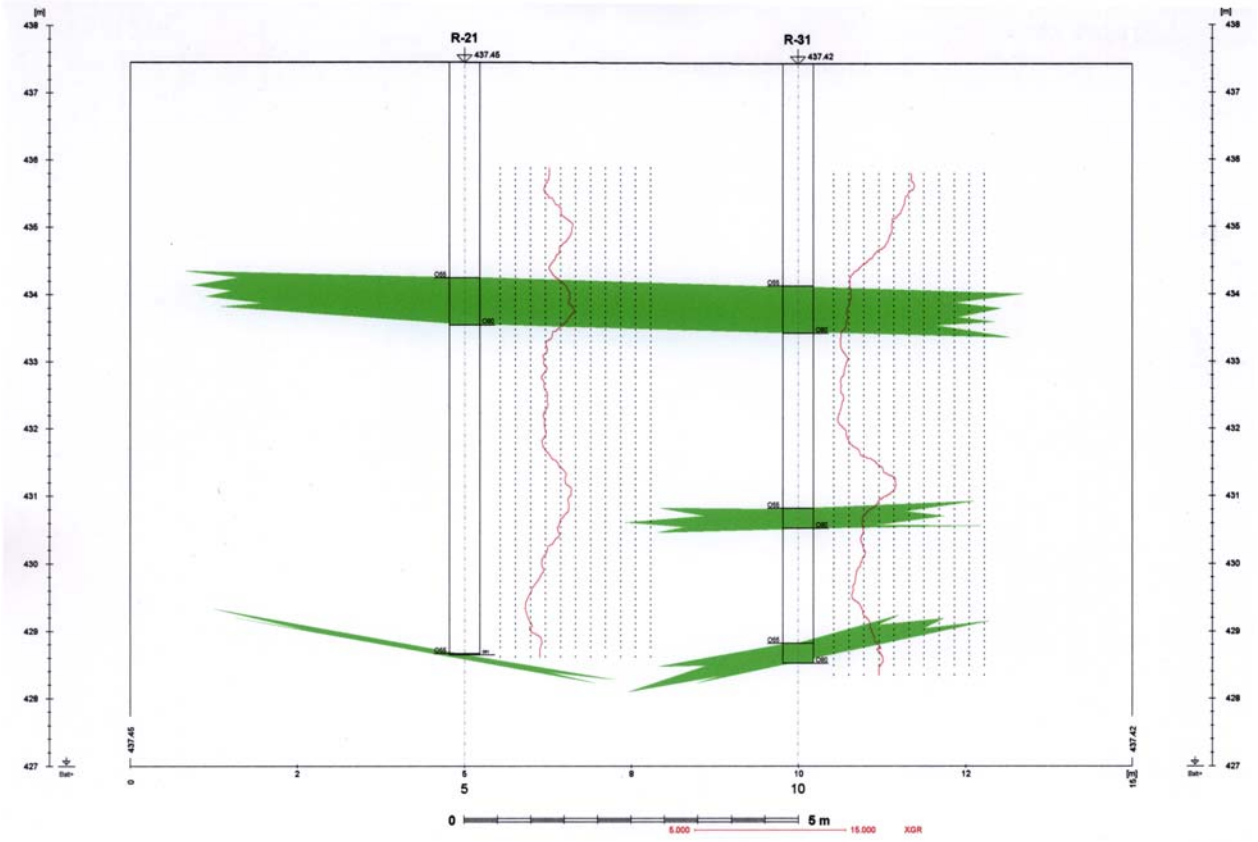

Figure 2. The course of permeable zones (fissures)

GROUNDWATER CONTAMINATION

The aquifer is contaminated by TPH and BTEX. The presence of the free phase on the groundwater table with the thickness of 15 mm was detected, the dissolved TPH were found up to 65 mg/L and benzene up to 13 mg/L.

REMEDIATION SYSTEM

The system of the remediation at the site is performed as the combination of the following four methods: 1) pump & treat method, 2) bioventing, 3) enhanced biodegradation, and 4) air-sparging.

The groundwater was pumped from three remediation wells (the system was adjusted during the duration of the remediation; only well R-21 was pumped last six months of the remediation). Regarding the low efficiency to clean-up the groundwater in the vicinity of old monitoring well B-106 by pumping of adjacent remediation well R-31 (in distance of 3 m from B-106) well B-106 was also occasionally pumped (four hours of pumping once or twice per month).

The treated water was partly discharged to the sewage system and partly accumulated in the accumulation tank where nutrients and an electron acceptor (oxygen) were added. The mixture of the treated water, nutrients and electron acceptor was discharged into the trench upstream of the groundwater flow. All three remediation wells were adjusted for bioventing (soil vapor extraction) that was carried out in the zone of the groundwater drawdown caused by the pumping. Further, air was injected into the aquifer through three air-sparging wells. The bubbling of the air through the saturated zone caused striping of aromatic hydrocarbons (BTEX), i.e. their transition into a gaseous phase. The contamination in the gas phase was captured by the combined remediation wells.

Due to the presence of the net of not interconnected fissures the emplacement of water pumps in the individual remediation wells together with the groundwater table drawdown showed to be very important for the efficiency of the remedial pumping.

RESULTS OF REMEDIATION

In the case of well R-32 the clean-up limits were reached already after one month without their exceeding during the rest of the remediation process. In the case of well R-21, the significant fluctuation of benzene and TPH concentration in the groundwater with the peaks manifold exceeding the clean-up limits was observed. Nevertheless, the clean-up limit was reached after 19 month of remediation (the decreasing trend of the contamination development could be traced). The TPH and benzene concentration in well R-31 were below reference values after 6 month of remediation with the exclusion of the single increase of TPH concentration after 17 months (not further appeared).

Occasional pumping of old monitoring well B-106 combined with other remedial methods used was sufficient to remove the free phase from the groundwater table and to reach the clean-up limits during 4 months of such system also in this well.

CONCLUSIONS

Regarding the multi-technological approach for the groundwater remediation the clean-up limits were reached within 1.5 years despite of the complex hydrogeological conditions (strongly heterogeneous fractured rock with not interconnected fissures and intergranular porous zone in the vicinity of the groundwater table).

Case study of geochemical stabilization of hexavalent chromium in groundwater

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A b s t r a c t : At many industrial sites and waste disposal sites in the Czech Republic, chromium has been released into the environment via leakage and poor handling during manufacturing or improper disposal practices. Industrial applications most commonly use chromium in the form of hexavalent Cr^{VI}, which is actually toxic and very mobile in groundwater. This article discusses a case study of an innovative technology (geochemical stabilization of hexavalent chromium in groundwater) at the test site, where chromium Cr^{VI} was used for the chrome-plating of tools.

INTRODUCTION

At the beginning of the 21st century society is passing through a dynamic era accompanied among other things by the stormy development of new technologies designed not only for facilitation of common life, but even for such a specialized branch, as contamination hydrogeology surely is. An integral part of the environmental creation and protection process in the Czech Republic is also the removing of anthropogenic pollution from the rock environment and groundwater.

This article discusses a case study of the innovative technology (geochemical stabilization of hexavalent chromium in groundwater) at the test site, where chromium Cr^{VI} was used for the chrome-plating of tools. Consequently the environment (saturated and unsaturated zones) has been contaminated by hexavalent chromium due to poor management of chemical agents. Concentrations of Cr^{VI} in the unsaturated zone exceeded 10 000 mg/Kg of soil. In the vicinity of the source zone investigation proved the extent of the plume to the groundwater level (approx. 9 meters below the surface). The main source of contamination was leaking sewerage.

Contamination of groundwater is bound in the deeper and partly fractured aquifer. Concentrations of Cr^{VI} in groundwater exceeded 50 mg/L in the source zone.

GEOLOGICAL AND HYDROGEOLOGICAL CONDITIONS

From the geological and hydrogeological point of view the site is a complex of two different units. Fluvial sandy gravel sediments of Berounka River create the younger and upper unit. The porous permeability is dominant. The groundwater surface in this unit is free or slightly confined. Average thickness of this unit is approx. 8 meters.

The second deeper and older unit is built by silty shale with local penetration of spilite and quartz porphyry. The fractured rock permeability is dominant in this unit.

The contamination is spread in both geological and hydrogeological units. More complicated for remediation works is the deeper fractured unit.

REMEDIATION WORKS AT THE SITE

A few remediation technologies were used at the site. Contaminated soil (unsaturated zone) near the surface was excavated. The amount of excavated contaminated soil was approx. 15 tons. Contaminated groundwater was pumped and treated through an ion exchange unit. This technology is still in use. The problem lies in the deeper and fractured part of the aquifer. Traditional pump & treat technology is not very effective in this type of media. This is the reason why geochemical stabilization was selected as an alternative remedial technology (see Fig.1).

The goal of this technology is to stabilize the source zone of Cr^{VI} in groundwater and contaminated soil into the more thermodynamically stable Cr^{III} form. The reduced chromium is expected to geochemically fix onto aquifer solids. The technology is based upon the concept of extracting contaminated groundwater and treating it above ground, followed by reinjection of the treated water into the aquifer. The reinjected groundwater is mixed with a reductant to reduce any residual Cr^{VI} contamination remaining in the interstitial water. The success of the *in situ* chromium geochemical stabilization technology depends on the ability of the applied reductant to reduce Cr^{VI} in groundwater to Cr^{III} and on the capacity of the reduced chromium to fix onto the aquifer solids.

CONFIGURATION OF REMEDIATION WELLS

Special emphasis was devoted to the design of injection and extraction wells. There is one group of 8 small diameter injection wells at the site. These wells are situated in the former source zone and reach to a few meters above the groundwater table.

Gravitational injection was selected as the best and most effective solution for the unsaturated zone, which is predominantly made up of sandy gravel sediments.

The extraction wells are situated in the direction of the groundwater flow. These wells are designed as classic hydrogeological wells with the plastic casing and open screens.

LABORATORY TESTS

Laboratory test were performed prior to practical application of stabilization on site. The column test was selected as the best simulation of “real” conditions. Water and soil samples for the test were collected on site. Four reductants were tested at the beginning. Sodium pyrosulphite gave the best results. This chemical agent is very well known from wastewater treatment, it is normally used. Contaminated water was mixed with pyrosulphite and gravitationally injected into the column.

Holding time (detention period) for water in the column was approx. 16 hour. This holding time was sufficient for simulating Cr^{6+} reduction on site.

Water was sampled for Cr_{total}, Cr^{6+} and sulphite concentration and pH at the outlet of the column. This analysis was made three times a day. Other, more detailed analysis, were performed before start and after the end of the column test. In this case we measured concentrations of cations (NH_4, Ca, Mg, K, Mn, Na, Fe), anions (Cl, NO_3, NO_2, F, HPO_4, SO_4), Cr_{total}, Cr^{6+} sulphite and pH. This more detailed measuring was mainly used for description of groundwater quality changes after addition of selected reductant and for the geochemical model calibrating.

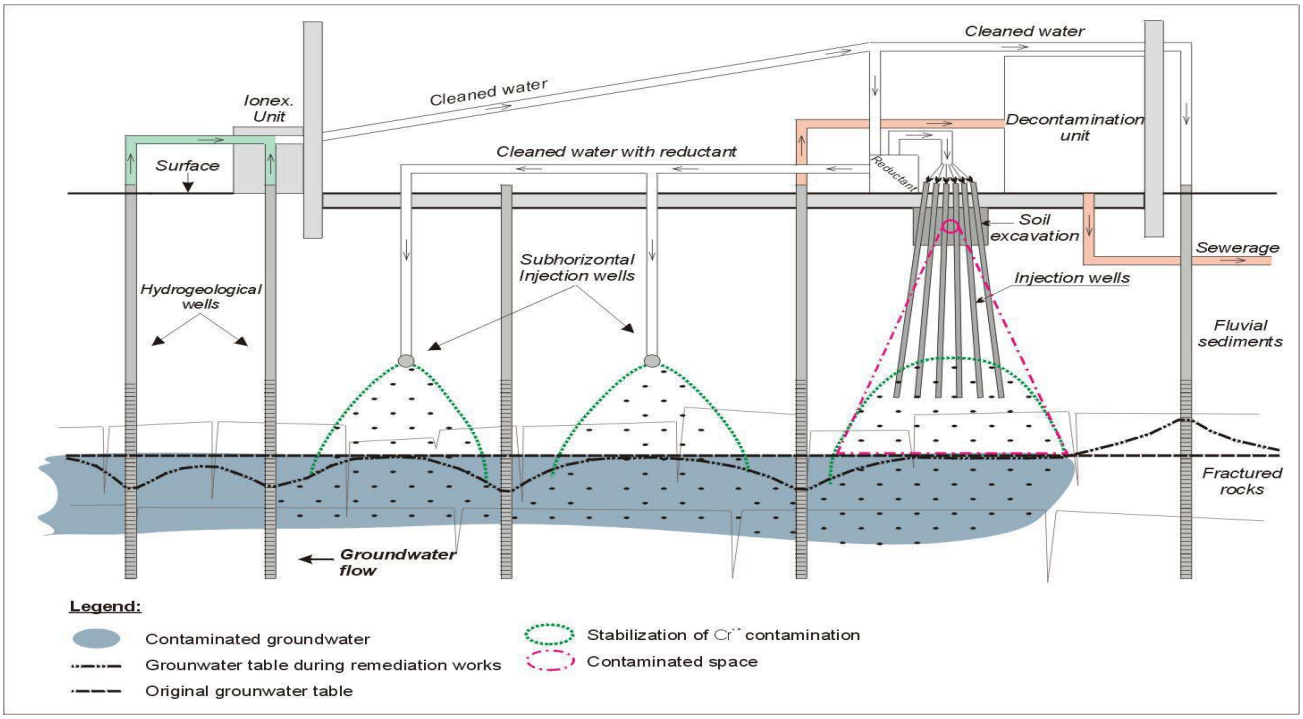

Figure 1. Design of the Cr^{6+} remediation on site

RESULTS

After laboratory tests including column and leaching tests, sodium pyrosulphite was selected as the best reductant in this case. The focus was placed on the amount of reductant (the less the better), reduction of Cr^{VI} concentrations, pH of groundwater and other geochemical parameters.

For a better description of stabilization processes on site we used the geochemical model MINTEQ A2. This model confirmed the results we obtained from laboratory tests. Practically all hexavalent chromium will be reduced to a stable trivalent form. More detailed results will be presented during the poster session at the conference.

REFERENCES

AQUATEST a.s.: Site Remediation Reports

Bartlett RJ (1991) Chromium Cycling in Soils and Water: Links, gaps and methods. Environmental Health Perspectives. Vol. 92 Pages 17 through 24

Henderson T (1994) Geochemical Reduction of Hexavalent Chromium in the Trinity Sand Aquifer. Groundwater, 33, pp. 759-768

Palmer CD, Puls RW (1994) Natural Attenuation of Hexavalent Chromium in Groundwater and Soils. U.S. EPA Ground Water Issue, EPA/540/5-94/505

Pitter P (1999) Hydrochemie. VŠCHT Praha, 3. vydání, ISBN 80-7080-340-1 (in czech)

U.S. EPA (2000) In Situ Treatment of Soil and Groundwater Contaminated with Chromium. Technical Resource Guide. EPA/625/R-00/005

Unlined bedrock tunnel as a solution to water-conveyance: effect of water on the long-term stability of fracture zones in the Päijänne Tunnel, Finland

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A b s t r a c t : Potable water to the Helsinki metropolitan area in Finland is conveyed along the mostly unlined, rock-surfaced Päijänne Tunnel. Two cave-ins in recent years and the inspection preceding the repair of the northern part of the tunnel in 2001 demonstrate impairment of its condition, probably influenced by the low initial level of reinforcement. Most of the damages, which concentrate to zones of existing weakness and unlined sections, result from weathering, swelling clays, erosion and changes in groundwater or pressure conditions. The main triggering factor is water that flows both in the tunnel and in the fractures of the surrounding bedrock. The pressure level of tunnel water and fracture properties affect groundwater inflow. The occurrence of large block falls and a high rate of groundwater inflow both correlate to some degree with the amount of steel-supported reinforcement. To reduce maintenance need, zones in bedrock that are prone to weathering should be identified and adequately reinforced.

INTRODUCTION

The 120 km Päijänne Tunnel, an unlined, pressurized bedrock tunnel in Precambrian granite and migmatites, conveying potable water to the Helsinki metropolitan area in Finland is subject to deteriorating effects of rock pressure, groundwater circulation and pressures exerted by water being conveyed. In the planning stage it was expected that the excavation of the tunnel in 1973-1982 would activate groundwater circulation in the fracture zones, enhancing weathering (Niini 1968). Groundwater inflow into the tunnel, caused by the tunnel water's pressure being mostly lower than groundwater table, is estimated to be 6 L/min/100 m on average, while in use (PSV 1999). A 36-m drop in the water pressure from north to south at the pumping station, located 56.5 km from the tunnel's southern end, is expected to affect the rate of inflow through a change in the hydraulic gradient. The two more substantial cave-ins in 1997 and 1998 occurred in fractured and inadequately reinforced zones of weakness in bedrock, inferred having been exposed to washing of clay from fractures by flowing water. Swelling clay, erosion caused by water flow in the tunnel and chemical weathering are factors that may cause cave-ins to occur (Mikkola and Viitala 1999). During the repair inspection, impairment of the tunnel's condition was observed particularly where extensive fracture zones intersect the tunnel. Most of the blocks detected had fallen within zones that lacked reinforcement (Manninen 2001). The initial reinforcement, which now is considered quite sparing, included shotcrete and rock bolts. In locations of poor rock quality, reinforced concrete with re-bars or steel-netted shotcrete was applied (Pokki 1979). Geological characteristics of locations of block-falls were studied to test a likely influence of the distribution, orientation and hydraulic activity of fracture zones cutting the tunnel on the occurrence of damage. As the southern part of the tunnel is also to be repaired in the coming years, methods of predicting locations of damage would prove useful.

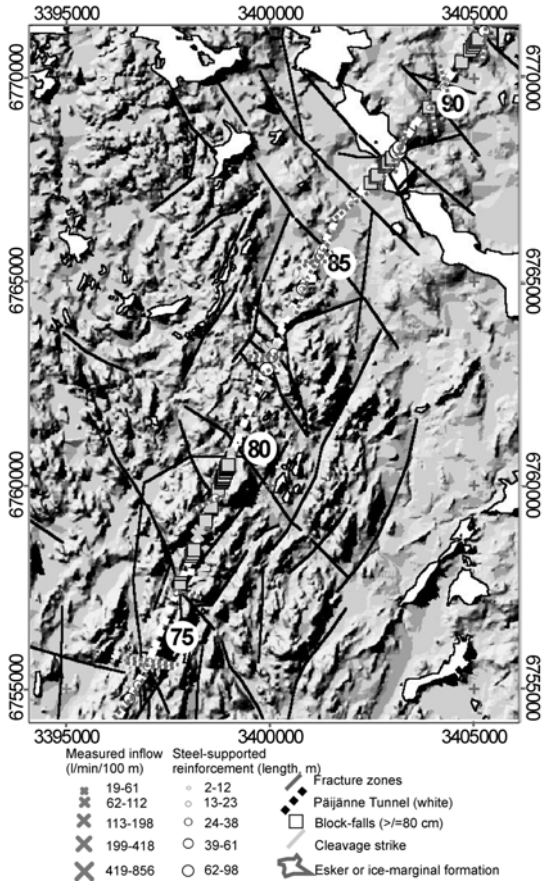

Figure 1. Spatial relationships of interpreted fracture zones, locations of measured groundwater inflow, steel-supported reinforcements and large (≥80 cm) block falls against the background of digital elevation model. The circled numbering refers to km from the southern end of the tunnel

METHODS

The general condition of the tunnel was investigated in 1998 and 1999 with a remote-controlled submercible robot by the company ASI (Mikkola and Viitala 1999). The number and size of fallen blocks was estimated from the video recording and used in planning the repair of the tunnel's northern 64 km, which took place in 2001. The total number of blocks, estimated for 72018-84800 (m from the southern end of the tunnel) includes the ones left lying after the tunnel was cleared for use for the first time. Some blocks were probably loosened by drilling and blasting, despite scaling, and fell afterwards. The occurrence of large blocks, 80 cm or more in length, is considered to better indicate damage in the tunnel than the total number of blocks many of which are small, less than 30 cm in diameter. The coverage of this large block data extends south from 28 km and north from 58 km. The number of large block fall locations was used instead for some comparisons. The accuracy of the distance measurement ranges generally 1-20 m but can be as much as 40 m.

The measured inflows represent the situation when the groundwater level was kept low by pumping and steeper hydraulic gradient enhanced the inflow. The curves of inflow

measured with weirs during the construction were available for the tunnel sections 466-84900. The 282 recorded locations of abundant inflow from 104 km southwards have essentially been treated in the spatial analysis as point data linked to the mid-point. The locations of cave-ins and large block-falls were visualised in GIS against the background of a digital elevation model, dominant cleavage strikes and lines representing fracture zones (Fig.1). Topography, seismic sounding profiles and observations from the tunnel were used iteratively in the fracture zone interpretation (Lipponen 2002). Despite the possible influence of different practices of contractors, steel-netted or bolted reinforcement is considered to indicate weakness in bedrock quite well. Each segment, 2 to 98 m in length, was represented by its mid-point in the spatial analysis. Due to the lack of type details for 112200-120000, total reinforcement amounts were used for the section in the correlation study.

RESULTS

The average rates of groundwater inflow into sections 58900-112200, measured during the repair, correlate linearly with both the total proportion of reinforced length (correlation coefficient

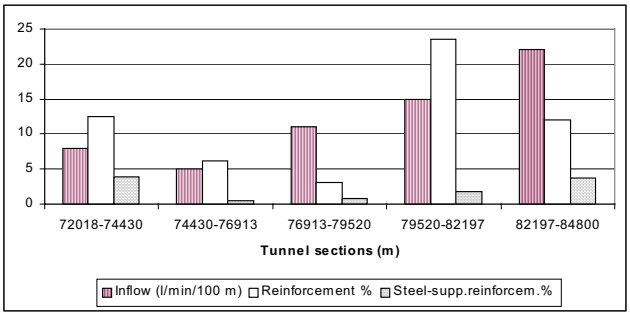

Figure 2. Groundwater inflow (L/min/100 m) and the proportion of reinforced length (%) distinguishing plain shotcrete and steel-supported reinforcement for five tunnel sections.

r=0.442, explaining 20% of the variation) and particularly with the proportion of steel-supported reinforcement (r=0.812, explaining 65% of the variation). For the southern part, the reinforcement at its highest only explains little more than 1% of the variation in the rate of inflow. Despite the same level of reinforcement in sections 72018-74430 and 82197-84800 (Fig.2), there is a 50 % difference in the total amount of block falls, indicating other contributing factors. The latter section has a high volume of inflow (22 L/min/100 m during construction) whereas in the former the inflow measured low. Of the sections 72018-84800, the ones with relatively little steel-supported reinforcement have the highest number of block falls.

Of the 167 locations of large block falls, 47 % were closer than 200 m to the interpreted fracture zones, 17 % closer than 100 m, or 71 % within a distance of 200-400 m. The proximity to fracture zones not fully explaining the occurrence of falls may be affected by 1) reinforcement of fracture zone intersections or 2) horizontal displacement of their surface projections from the tunnel depth, (30-130 m). In measures of a fracture zone valley (Niini 1968), 50 or 100 m from the centre can in many occasions be well within the fractured zone. A small angle between the tunnel's orientation and the strike of cleavage seems to be associated with large block falls: out of 167 falls, in 35 % the angle is smaller or equal to 10 degrees, in 58 % the angle is within 20 degrees or in 80 % within 40 degrees. The dominance of steeply-dipping cleavages at fall locations probably simply reflects the structural geology of the tunnel line.

The occurrence of large block falls per tunnel section shows a weak negative correlation with the amount of steel-supported reinforcement (n=18). No linear correlation was observed for average values of tunnel sections. A third of large block falls (n=106) observed within the measured inflow coverage is within 50 m of an inflow and 55 % are within 200 m. When the orientation of fracture zones closest to measured inflows was analysed (n=107), some of the highest rates of inflow appear to be associated with fracture zones striking NW or ENE. The highest 9% of the inflow rates occurred within 130 m of fracture zones. No consistent connection was observed between abundant fall of large blocks and the main groundwater reservoirs in the overburden such as eskers.

CONCLUSIONS

Groundwater inflows, cleavage strike sub-parallel to the tunnel and occurrence of block falls outside the heavily supported sections were identified characteristic of several individual tunnel sections in which large block falls had occurred in a greater number. Not all locations that on technical grounds require support have associated groundwater inflow, but an increased amount of fracturing in bedrock generally provides more flow paths to water. Only in the northern part of the tunnel where the pressure difference to groundwater and rates of inflow in general are higher, significant correlation of reinforcement with the rate of inflow could be demonstrated. Both the falls of large blocks and a high inflow are to some extent connected to heavy reinforcement indicative of weakness in bedrock such as frequent fracturing. As a direct correlation between the two could not be demonstrated here, it cannot be stated that block falls had preferentially occurred in hydraulically active tunnel sections. This may be affected by averaging of the highly localised inflows and block falls over 2.5 km tunnel drives.

Even when sealed to leaching groundwater flow by weathering into clay, a fracture is still prone to physical weathering caused by the tunnel water unless covered by protecting shotcrete. Fracture zones that appear as linear depressions in topography are potentially difficult from the technical support or groundwater inflow management points of view, but the hydraulic properties of fracture zones do vary despite a similar topographic appearance. Horizontal or low-angle fractures, which in general are difficult to detect from the surface, have been observed to leak groundwater into the Päijänne Tunnel at many locations, particularly in granitic rocks. The hydraulic properties of fracture zones are inferred to contribute to the deterioration of tunnel, but as a relatively minor factor, compared with the technical support solutions and structural orientation. For mitigating damage through appropriate reinforcement, fracture zones especially with associated inflow should be identified and characterised. The deterioration of the Päijänne Tunnel demonstrates that the dynamic environment causes maintenance need to emerge, albeit not frequently. It took 15 years of constant use before the first substantial cave-in took place and the increased reinforcement after the repair reduces exposure to weathering.

REFERENCES

Lipponen A (2002) Detection of potential pathways for contaminants into the Päijänne tunnel in Finland. Geological Survey of Norway Bulletin 439:27-32

Manninen S (2001) Vesitunneleiden vaurioitumisprosessit (English abstract: Failure processes of water tunnels). Helsinki University of Technology, Lab of Rock Engineering, 134 pp

Mikkola J, Viitala R (1999) Pitkien vesitunneleiden sortumat ja lujitus (English abstract: Cave-ins and reinforcement in long water tunnels). Helsinki City Real Estate Department, Geotechnical Division. Geoteknisen osaston tiedote 80:130 pp

Niini H (1968) A study of rock fracturing in valleys of Precambrian bedrock. Helsinki. Fennia 97(6):60 pp

Pokki E (1979) The Päijänne Tunnel. In: Maevis AC, Hustrulid WA (eds) Proc.of Rapid Exc.and Tunn.Conf.: vol.1 Soc of Min Eng, Am Inst of Mining Met and Petrol Eng Inc, NY, 1175-1185

PSV (1999) Annual report 1998 (in Finnish). Pääkaupunkiseudun Vesi Oy (Helsinki Metropolitan Area Water Company), 59 pp

Dynamic and transient simulation of the free groundwater table at Olkiluoto, Finland, using an automatic, adaptive mesh generator FEFTRA/octree

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The candidate site for the disposal of spent nuclear fuel Olkiluoto (Finland) has been subject to extensive field and modelling research conducted by the Finnish nuclear waste company Posiva Oy. One of the research programmes includes the construction of a complex system of drifts in the crystalline fractured granitic bedrock, consisting of a downward spiralling access tunnel, a ventilation shaft and research facilities at 420 m and 520 m below sea level. The construction and the operation of these facilities constitute a major hydraulic stress for the site's groundwater regime.

In this study we assessed the hydraulic impact of the drift system with a numerical model. The evolution of the depression area of irregular shape was simulated in a heterogeneous geological environment, and its horizontal and vertical extent was determined. The numerical tools for the simulations were developed at VTT Processes.

In fact, the shape of the saturated zone, including its moving, upper bounding surface was simulated in a time-dependent manner. Each time step consisted of a meshing phase and a finite element analysis phase. The two phases provided the discretised computational domain and its updated upper boundary, respectively, to each other.

In the meshing phase the modelled volume was recursively subdivided into a set of cubes using the efficient octree algorithm. Local refinement was developed around natural and engineered bedrock structures, as well as at the actual free surface. The cubes were converted into tetrahedra that are applicable in finite element calculations. Identified, large fracture zones were represented with triangles of given hydrologic properties befit over the faces of appropriate tetrahedra along their planes. Elements that fall above the free surface (i.e. were not part of the saturated zone) were removed from the model, and the mesh was passed to the finite element simulator

In the finite element analysis phase the hydraulic head distribution was determined with a two-stage implicit scheme suggested by Huyakorn and Pinder (1983). The drifts were represented with prescribed constant head boundary conditions at the nodes falling along their geometry. At the end of the time step, the new position of the free surface was updated with the hydraulic head field at the actual nodes of the free surface. This process was repeated until the free surface reached an equilibrium position, in which the saturated zone received as much water from its external boundaries as it lost through its internal sinks.

We found that without grouting the drift walls the free surface sank into a depth of about 300 m below sea level, while with grouting (modifying the hydrologic properties of the elements adjacent to the drift walls) this impact can be decreased by an order of magnitude (34 m). The simulated results qualitatively agree with field conditions observed in similar rock laboratories elsewhere in the world, and the shape of the simulated free surface faithfully follows the given heterogeneities of the modelled rock.

REFERENCE

Huyakorn PS, Pinder GF (1983) Computational Methods in Subsurface Flow. Academic Press Inc

The essential geology and hydrogeology for 92km of tunnelling, Austria/Italy

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A b s t r a c t : The geology of Tyrol is a complex stack of nappes consisting of mainly low and high grade metamorphic rocks of magmatic, volcanic and sedimentary origin and sedimentary rocks of marine and terrestrial origin, the result of compressional and extensional poly-phased ductile and brittle phases of deformation related to the various stages of the ongoing Alpine Orogeny. This geological framework is the setting for various complex hydrogeological systems, which contain groundwater of very varying physical, chemical and isotopic character. At present, the approx. 400km long Railway Project Munich-Verona, is being planned and built. An overview of the hard-rock geology and hydrogeology for two sections of this project is presented. Detailed aspects of the hydrogeological investigations can be found in this volume (Burger *et al.* 2003, Fisch *et al.* 2003, Reichl *et al.* 2003).

DATA ACQUISITION - METHODOLOGY

In both sections of the railway project large-scale and intensive geological and hydrogeological investigation programmes (mapping, geophysics, cored exploratory wells, hydraulic tests, etc.) have been carried out. Five reconnaissance tunnels were constructed in Brixlegg and Vomp from 1999-2002 (Poscher *et al.* 2002). Since 1996, app. 1500 hydrological measuring points (springs, commercial and exploratory wells, surface/rain water) have regularly been monitored and sampled.

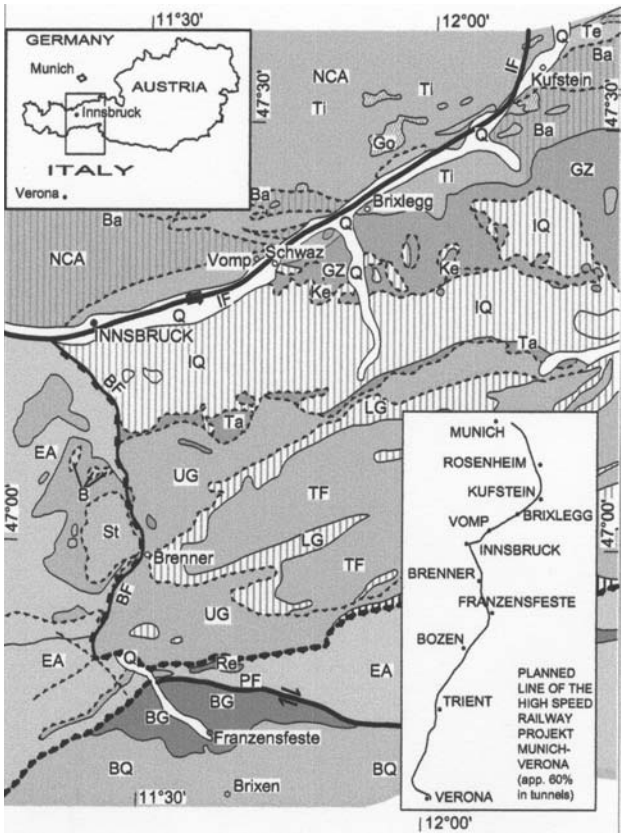

Figure 1. Geologic overview map of project area (modified from Brandner 1980). Main tectonic units are (N to S): Northern Calcareous Alps (NCA) including Inn Valley Tertiary (Te), Gosau Group (Go), Tirolikum (Ti) and Bajuvarikum (Ba) Nappes; Greywacke Zone (GZ); Kellerjoch Gneiss (Ke); Innsbruck Quartz-Phyllite (IQ); Nappes of the Tarntal Zone (Ta); Austroalpine (EA); Brenner Mesozoicum (B); Steinacher Nappe (St); Glockner Nappe (UG); Venediger Nappe (LG); Central Gneiss (TF); Periadriatic Intrusives (Re); Brixen Granite (BG); Brixen Quartz-Phyllite (BQ). Major labelled faults are: Inn Valley Fault (IF); Brenner Fault (BF) and Puster Valley Fault (PF) (Ortner *et al.* 2001). Also shown is the extent of the Quaternary (Q) filled valleys which are several hundred metres deep. Insertions show project location (upper left) and railway line trace (bottom right)

GEOLOGIC OVERVIEW FOR 92KM OF TUNNELLING

The two sections of the railway project cross the Alps, Tyrol. The first, which is presently being built, is 42km long (80% tunnels) and follows the trace of the Inn Valley Fault (IF) from just NNE of Brixlegg to Innsbruck. It contains two major hard rock tunnel sections at Brixlegg (4.1km) and Vomp (3.4km) within the Northern Calcareous Alps (NCA) and Greywacke Zone (GZ). The second, the deep-lying Brenner Base Tunnel (app. 60km), which is at the preliminary planning and exploratory phase, is planned to penetrate several major tectonic units and cross major faults of the Alps to the east of and below the Brenner Fault (BF) from Innsbruck, Austria to Franzensfeste, Italy (fig.1).

HYDROGEOLOGY AND WATER CHEMISTRY

Tab.1 shows the major geologic formations and groups to be penetrated by the tunnels. Aspects of their hydrogeological behaviour and typical water chemistry are given. The Quaternary (Q) sequences (mainly unconsolidated alluvial and glacial - not described in tab.1) and the aquifers they contain, interact with the hard rock aquifers resulting in complex hydrogeologic systems.

Along with the primary porosity, the ubiquitous faults and open fractures also play a major role in controlling groundwater movement. The faults can act as aquitards as well as aquifers (fault zones), sometimes displaying very high porosity and permeability (Fisch *et al* 2003).

Water chemistry and isotopic properties (e.g. $\delta^{34}S$, ^{3}H, $\delta^{18}O$) are heavily dependent on the lithological compositions of the source-aquifers, residence times and groundwater flow systems.

REFERENCES

Brandner R (1980) Tektonische Übersichtskarte von Tirol 1:600.000, Tirol Atlas, Universitätsverlag Wagner, Innsbruck

Burger U, Millen B, Brandner R (2003) Northern section of the Brenner Base Tunnel - hydrogeological remarks. This volume

Fisch H, Mammel R, Poscher G, Reichl I (2003) Methods of fractured aquifer characterisation. This volume

Ortner H, Reiter F, Brandner R (2002) Kinematics of the Inntal shear zone and its relation to other major faults crossing the N TRANSALP seismic section. Mem Sci Geol 54:189-192

Poscher G, Fisch H, Mammel R, Sedlacek C (2002) Konfliktfeld Untertagebau und alp. Wasserressourcen. Felsbau 20:101-111

Reichl I, Mammel R, Kech M, Poscher G, Fisch H (2003) Temporary artificial draw-down of a joint aquifer. This volume

Table 1. Formations and groups to be crossed (N to S). Geology, hydrogeological behaviour and water chemistry is shown

TC	Map Unit/Nappe	Fm./Gr. [Age]	Geology	Hydrogeological Behaviour	Typical Water Chemistry
Upper Austroalpine	Northern Calcareous Alps (NCA) - Tirolikum (Ta) & Bajuvarikum (Ba) Nappes	Hauptdolomite Fm. [Tr(Nor)]	mainly b&m dol; intensively fractured	form along with the Wetterstein Fm. (WF) the main aqf. in NCA, seq. up to 2500m thick - H_2O-cond. over p-space/bed & f/f; longer ret. time ($\delta^{18}O$, ^3H results) than WF	dol: 300-400µS/cm; Ca55%-Mg45%-$HCO_3$95%; Ca/Mg Ratio app.1.2
		Raibl Gr. [Tr(Crn)]	lst, dol, slt ± sst ± mrl ± rw; imp. in major d/t horizons	slt & mrl act as aqt. except when fractured, dol, lst & rw as aqf.; rw (evaporite) commonly has sol-cavities & k-behaviour; commonly chem. overprint H_2O from other aquifers due to presence in faults	rw-source (spa-water): 1500µS/cm; Ca75%-Mg22%-$SO_4$72%-$HCO_3$27%; app. 660mg/L SO_4; $\delta^{34}S$ app. +15‰ VCDT; slt-source: 600-700µS/cm; Ca50%-Mg40%-$HCO_3$75%-$SO_4$20%; 60-70 mg/L SO_4; $\delta^{34}S$ 0 to -6‰VCDT
		Wetterstein Fm. [Tr(Lad/Crn)]	b&m lst, dol	along with the Hauptdolomite Fm. (HD) the main aqf. in NCA, up to 1500m thick - H_2O-cond over p-space/bed & f/f & sol-cavities; k-behaviour; outflows >100 L/s common; shorter ret. time ($\delta^{18}O$, ^3H results) than HD	lst: 150µS/cm; Ca70%-Mg30%-$HCO_3$95%; Ca/Mg Ratio app. 2.3 and sometimes greater
		Partnach Fm. [Tr(Lad/Crn)]	slt, mrl, lst ± sst	aqt.	n.a.
		A.Muschelkalk Gr. (var. Fms.) [Tr(Ans/Lad)]	b-m dol, lst	n.a. to this study - however form imp. aquifers in NCA; k-behaviour	n.a.
		"Reichenhall Fm." [Tr(Scy/Ans)]	mainly dol ± rw ± mrl ± lst; imp. in major d/t horizons	mrl act as aqt. except when fractured; dol, lst & rw as aqf.; rw (evaporite) commonly has sol-cavities & ?k-behaviour; commonly chem. overprint H_2O from other aquifers	rw-source (min-water): >1000µS/cm; Ca80%-Mg13%-$SO_4$80%-$HCO_3$13%; up to 1000mg/L SO_4; $\delta^{34}S$ app.+23 ‰VCDT
		Alpiner Buntsst. / Grödner Fm. [Tr(Scy)] / [P]	sst, cgl ± rw; imp. in major basal d/t horizons	generally acts as aqt.	source of K-rich H_2O (up to 5%)
	Greywacke Zone (GZ) (meta-basement)	Schwazer Dolomite [D]	dol with sufidic-fahlore	aqf. - H_2O-cond. over p-space/bed & f/f; secondary H_2O-cond. due to mining practices	450µS/cm; Mg45%-Ca45%-$HCO_3$70%-$SO_4$25%; Sb-content (up to 1mg/L); Ca/Mg Ratio app. 1
		Wildschön-auer S. [O_1-S_2]	pyl, qzt	aqt. except when brittlely deformed	230-330µS/cm; Ca65%-Mg25%-$HCO_3$90%; Ca/Mg Ratio app. 2.6
	(local occurrence-not marked on map)	Mauls Triassic [Tr]	mainly dol, slt ± rw ± sst	aqf. however no known surface outflows; conductive in deep boreholes	in boreholes: >1000µS/cm; Ca-Mg-SO_4 type water
	Austroalpine (EA) (cryst. basement)	Ötztal-Stubai & Defregger Cmplx. [?Pz_1]	mainly gns, sch ± amb	aqf. when brittlely deformed	100-200µS/cm; Ca/Mg Ratio app. 3.0
Lower Austroalpine	Nappes of the Tarntal Zone (Ta)	various Fm. [P-Mz], (tectonic melange, overlying IQ)	mainly ca-rich sch, sil-lst, dol, mab ± srp ± rad ± slt ± rw ± qzt	carbonates form primary aqf.; deep-reaching H_2O circulation over f/f; rw (evaporite) is soluble	350-400µS/cm; SO_4 app. 35mg/L rw-source; Ca/Mg Ratio app. 2.0
	Innsbruck Quartz-Phyllite / Patscherkofel Crystalline (IQ) (meta-basement)	Innsbruck Quartz-Phyllite /Patscherkofel Crystalline [?Pz_1]	mainly q-pyl ± gns ± sch ± amp ± mab	generally has poor H_2O-cond., however weathered, faulted & fractured zones form numerable important aqf. with small outflows (<10L/s)	q-pyl: 100-200µS/cm; Ca75%-Mg17%-$HCO_3$75%-$SO_4$17%; Ca/Mg Ratio app. 4.4; gns: 20-100µS/cm; Ca65%-Mg20%-$HCO_3$75%-$SO_4$20%; Ca/Mg Ratio app. 3.25; high K & Na content (5-10%)
Penninicum (Tauern Fenster)	Glockner Nappe (UG) "Obere Schieferhülle"	"Nordrahmen Zone" [J-K] (exotic blocks)	mab, cal-pyl, ca-poor sch dol, rw, qzt, srp, oph	intensely tectonised (lies in major d/t horizon), H_2O-cond. generally over f/f systems; presence of exotic blocks alters water chemistry	400-500µS/cm; SO_4 content app. 25mg/L; Ca/Mg Ratio app. 0.9
		Bündner Schiefer [J-K]	cal-sch, ca-poor sch ± mab ± meta-oph ± ply	very var. behaviour, higher permeability in cal-sch, H_2O-cond. generally over f/f systems	very var. H_2O-chem; ca-rich sch-source Ca/Mg Ratio app. 5.0, ca-poor sch-source app. 2.3; app. 300µS/cm is typical
	Venediger Nappe (LG) "Untere Schieferhülle"	Modereck Nappe [P-K_2] and Tulver-Senges Unit [P-Tr]	mainly, lst, mab, dol, rw ± qzt ± meta-ark ± pyl	aqf. - H_2O-cond. over pore space/schistosity & f/f; mab, dol & rw commonly has sol-cavities, deep-reaching k-behaviour	very var. H_2O-chem; 200-1000µS/cm; Ca/Mg Ratio 1-2; some outflows SO_4 content is 300mg/L, rw-source; $\delta^{34}S$ app. +12-14‰VCDT; high K-content from meta-ark
		Hochstegen Zone [P-K_2]	mainly mab, dol ± qzt ± meta-ark ± pyl	aqf. - H_2O-cond. over pore space/schistosity & f/f; mab & dol commonly have sol-cavities, k-behaviour; large outflows app. 10-100L/s exist	mab, dol: 170-300µS/cm; Ca80%-$HCO_3$85%; Ca/Mg Ratio app. 4.7
	Central Gneiss (TF)	Central Gneiss [P]	granite-gns	aqf. when brittlely deformed and weathered; at several 100m depth (boreholes) conductive	at shallow depths app. 100µS/cm, Ca/Mg Ratio app. 10; boreholes: >1000µS/cm, Ca-Na-SO_4-Cl type water, origin not clarified
S. A.	Brixen Granite (BG)	Brixen Granite [P]	grn	aqf. when brittlely deformed and weathered	<100µS/cm; moderate K & Na content; Ca/Mg Ratio 3-10

Abbreviations (alphabetical order): % molar-% cations-anions; A. Alpine; amb amphibolites; aqf. aquifers; aqt. aquitards; ark arkose; b&d bedded and detrital; b&m bedded and massive; b-m bedded to massive; brc breccia; cal calcareous; ca–poor carbonate–poor; ca-rich carbonate–rich; cgl conglomerate; chem chemistry: d/t detachment/thrust; dol dolomite; f/f faults/fractures; Fm. Formation; gns gneiss; Gr. Group; grn granite; H_2O-cond. water conductivity; k karstic; lst limestone; mab marble; mrl marls; n.a. not applicable; oph ophiolites; p-space/bed pore space/bedding pyl phylitte; q quartz; qzt quartzite; rad radiolarite; ret retention; rw rauhwacke; S. Schiefer; S.A. Southern Alpine, sch schist; seq. sequences; sil siliceous; slt slates; sol solution; srp serpentinite; sst sandstones; TC tectonic complex; var. variable

Groundwater protection downgradient from a sludge lagoon of the Rozna uranium deposit, Czech Republic

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A b s t r a c t : The objective of hydrogeological investigation was to control the leakage of the waste water contaminated by sulphates and uranium from the sludge lagoon at the uranium deposit in Rozna (Czech Republic). The sludge lagoon is located over the fractured moldanubic rocks. The surface geophysics was carried out to identify the preference contaminant pathways. The hydraulic properties of the identified fractured zones were verified by the pumping tests. Groundwater sampling and groundwater monitoring were conducted to assess migration of contaminants. The vertical distribution of contaminants was determined by means of borehole logging. The system of interceptor wells was proposed to protect the groundwater quality downgradient of the lagoon.

INTRODUCTION

The uranium deposit in Rozna has been operational since 1957. The sludge lagoon associated with ore preparation has been operational since 1968. Both are finishing the operation. The rock complex at the Rozna deposit consists mainly of the moldanubic rock represented by plagioclase-biotite-amphibolite gneiss and amphibolites. The other rocks are marble, small bodies of serpentine and pyroxene. The rocks are weathered to the depth of 20 m. The upper weathered layer is formed by clay and soil clay reaching the thickness of about 3 – 7 m. The waste associated with ore preparation was disposed of to the sludge lagoon. It is located between two dikes and has not been engineered. The sludge consisting of very fine particles was transported hydraulically to the lagoon by the system of pipes. The water infiltrated through the lagoon bottom was partially intercepted by the drainage system and returned back to the lagoon. The system of monitoring wells has been established downgradient of the lagoon. The contaminant plume with high concentration of sulphates up to 3 g/L and moderately elevated concentration of uranium up to 0.2 mg/L has been detected in groundwater.

The objective of hydrogeological investigation was to propose the effective groundwater protection measures to control the leakage from the sludge lagoon to groundwater. It was divided into the following phases: identification of the preference contaminant pathways downgradient of the lagoon, determination of their hydraulic properties, definition of the groundwater flow direction, contaminant plume delineation and development of groundwater protection measures

METHODOLOGICAL APPROACH

The surface geophysics was conducted to identify the preferential migration pathways. The following methods were applied: dipole electromagnetic sounding, very long waves (electromagnetic and resistance), vertical resistivity sounding (VES) and georadar. Monitoring wells were installed in the identified fractured zones. The objectives of these installations were as follows: to prove the existence of fractured zones identified by the geophysical survey, to provide the data on the hydraulic properties of the aquifer and to extend the existing monitoring network used for groundwater sampling and groundwater level measurements. In each of the new monitoring wells a borehole logging was carried out to determine the fractured layer location and the vertical distribution of contaminants. The following methods has been used to this logging: GR gamma rey (measurement of the natural gamma radiation), LL3 3 electrode laterlog (measurement of rock resistivity in focused array), NNL neutron – neutron logging (measurement of rock porosity), RM measurement of resistivity, DL gamma – gamma density logging (measurement of rock density), TEMP thermometry (measurement of temperature of borehole fluid), CAL measurement of borehole diameter. The pumping test was performed in all new monitoring wells to determine the hydraulic properties of the aquifer. The direction of groundwater flow was determined from the watertable contour map and more precisely by using “charged body” geophysical method. Regression analyse has been applied to determinate the hydraulic connection between different fissured zones. The long term groundwater quality monitoring results were proceeded statistically. All the data obtained were used for the development of the interceptor well system to control the contaminant migration downgradient of sludge lagoon. The multiple pumping test was conducted to prove the efficiency of the proposed system.

RESULTS

The results of all geophysical methods applied indicated that there are blocks of massive rocks without considerable fissured zones located downgradient of the lagoon. The fissured zones divided the blocks. Three northwest-southeast fissured zones radial to the lagoon were identified. These results correspond well to the previous information on geological structure of the region including the data derived from excavations and other activities. In addition, another fissured zone, situated parallel to south segment of the sludge lagoon at a distance of about 200 m has been identified. All fractured zones were verified by monitoring wells drilled to the depth of 20 - 30 m. The borehole logging results classified the rocks in the fractured zones as intensively fractured. Only in one fissured zone were reached the slight fractured rocks. Pumping tests conducted in new monitoring wells confirmed the slight conductivity values of the aquifer (conductivity about $3x10^{-6}$ m/s) and very slight conductivity ($6x10^{-7}$m/s). This values were determined in one radial fractured zone and correspond well to the borehole logging results. Groundwater flows from the west to the east and this direction was confirmed by “charged body” geophysical method. The real groundwater flow velocity of 0.7 m/day was determined by the same method. In the southwest-northeast fissured zone parallel to the lagoon, water table elevations were higher than those near the lagoon, and this prevents contaminant migration to the south. The regression analysis confirmed high hydraulic connections between groundwater levels in the monitoring wells located in different fissured zones. The only exception was observed in the monitoring well 518, installed in the above mentioned fractured zone with the slight conductivity value.

Sulphates and uranium contaminate groundwater downgradient of the lagoon. The borehole logging confirmed the vertical distribution of the sulphates concentration only in one monitoring well (519). In this well sulphate concentration was up to 1,020 mg/L at the depth of 4 m bellow the surface and up to 2,040 mg/L at the depth of 23 m below the ground surface.

Uranium concentration changed from 0.010 mg/L to 0.032 mg/L at the same depths. In the rest of monitoring wells vertical distribution of contaminant concentrations was negligible. The average annual sulphate concentration in the plume ranged from 1,287 mg/L to 3,415 mg/L with an average value of 2,370 mg/L. Uranium concentration ranged from 0.010 mg/L to 0.099 mg/L with an average value of 0.025 mg/L. However, in 70% samples taken uranium concentrations varied in the range of 0.010 – 0.018 mg/L only.

PROPOSE OF THE GROUNDWATER QUALITY CONTROL

The multiple well system was proposed to control migration of contaminated groundwater. The system design was based on the assessment of pumping test results, regression analysis of groundwater level fluctuations and vertical contaminant distribution in wells. The proposed multiple well system was verified by the 30 day pumping test. Groundwater discharge in different wells varied in the range of 0.008 – 0.12 L/s (the mean value of 0.08 L/s), while the drawdown was up 57 – 65 % of the aquifer thickness. The radius of influence was about 200 m. The high daily precipitation of 28 mm during the pumping test caused the temporary rise of groundwater levels in the pumped wells after 20 – 40 hours. During the pumping test concentration of sulphates decreased by 51 – 84 % and at the end of pumping test it was in the range of 832 – 2,386 mg/L with an average value of 1,668 mg/L. After finishing the pumping test sulphate concentration recovered to their initial values. Similarly, uranium concentrations decreased by 20 – 90% during the pumping test and recovered after it was ceased. The decrease in concentrations for both contaminants was smaller than the mean concentration for the last two years. The only exception was the concentration changes for both parameters in well 519. We mentioned above that the well 519 is the only one where vertical distribution of contaminants has been observed. Sulphate concentrations in this well increased during the pumping test from 1,520 mg/L to 1,990 mg/L and uranium concentrations from 0.010 mg/L to 0.044 mg/L. After finishing the pumping test both of them recovered to their original values. It could be explained by the presence of higher concentration at the bottom of the well. The decrease in contaminant concentrations was also observed in two monitoring wells (517 and 509 D), located outside of radius of influence. In this case the decrease in concentrations was caused by dilution of contaminants in groundwater after decrease of concentrations in pumped wells. Concentration of both contaminants increased to the initial values after the pumping test has been ceased.

The groundwater control system proposed was based on the results of the multiple pumping test. It was shown that multiple pumping of 5 wells with total discharge of 16 m^3/day can intercept groundwater contaminated by sulphates and uranium and prevent the migration of contaminated groundwater downgradient of the lagoon. In addition, the decrease in contaminant concentrations due to pumping is expected.

After finishing mining activities the sludge lagoon will be descommissioned and unpolluted run–off will be discharged to the nearest stream.

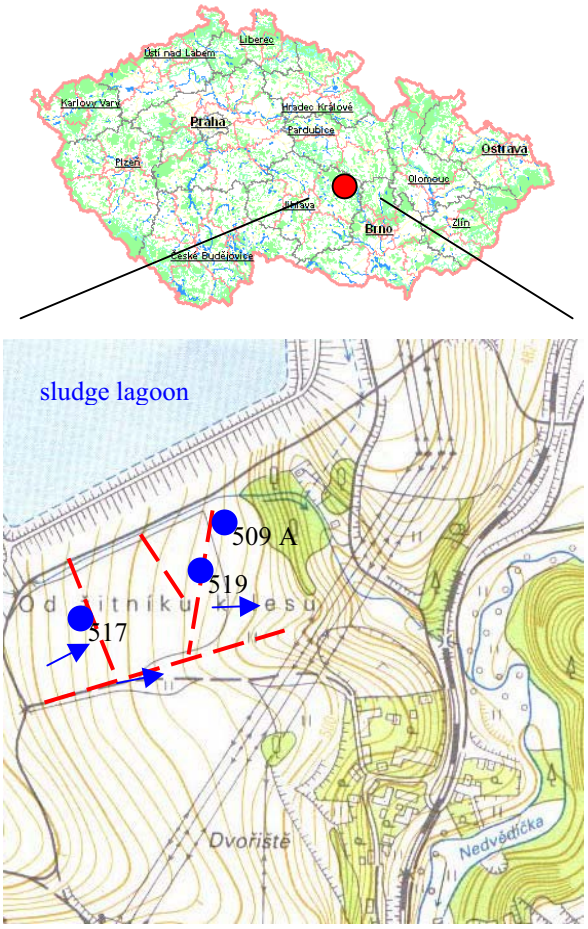

Figure 1. Location of the study region

Scale: 1 : 10,000

9 **Monitoring well (mentioned)**

Fractured zone

Direction of groundwater flow

CONCLUSIONS

The comprehensive hydrogeological and geophysical investigation with the aim to propose the groundwater quality control system downgradient of the sludge lagoon at the Rozna uranium deposit have been conducted. This approach enabled to assess very complicated hydrogeological conditions and develop the efficient groundwater quality control system.

Multiple pumping in 5 wells with total discharge of 16 m^3/day will intercept contaminated groundwater flow and prevent contaminant migration. Concentrations of main pollutants (sulphates and uranium) will decrease to the acceptable levels.

Identifying the sources of different pollutants to municipal wells in hard rock, SE Sweden

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A b s t r a c t: Very high Cl concentrations, high Pb concentrations, raised Cd- and Zn concentrations and bacterial pollution have been observed in a municipal water supply based on three drilled wells. In this paper the emphasis is on Pb that have had concentrations close to and once above the limit for drinking water quality. However, the concentration in the drinking water distributed to the consumer has been low due to treatments in the waterworks. Several possible sources of Pb exist in the area: natural enrichment in the till and the bedrock, road traffic pollution, long-distance transported pollution and a dumping site for glass slag. Analysis of the $^{206}Pb/^{207}Pb$ ratios showed that none of the anthropogenic sources alone could explain the raised Pb concentration. The lower groundwater level when the Pb concentrations were high suggested that a certain mixing of groundwater dominated at that occasions.

INTRODUCTION

The municipal water supply of the village Målerås, Nybro municipality, SE Sweden, is based on three wells drilled in porphyry rock. The wells are located close to a hihgway (30-100 m) in the outskirts of the village and 1.2 km S of a glasswork with its own drilled well. The groundwater in the municipal wells has been polluted by a variable, but sometimes very high concentrations of chloride (max. 405 mg Cl/L) since the beginning of the 1990´s and by coli bacteria (even E.coli) during shorter periods during the last years. Occasionally high concentrations of heavy metals (Cd, Pb and Zn), for Pb close to and once above the limit for drinking water quality, have been observed in the wells. The objective of the study has been to identify the sources of the pollutants by different methods. In this extended abstract emphasis is on the raised concentrations of heavy metals, in particular Pb. Several sources of Pb exist in the area: natural enrichment in the till and Galena-mineralization in the bedrock (SGU 1992; Sundblad 1997), road traffic pollution, long-distance transported aerosols, old local air transported pollution from the glasswork and old as well as new dumping of glass slag. An additional factor to consider is that the use of de-icing salt increases the Pb mobility (Norrström and Bergstedt,2001)

METHODS

The study started with collection and evaluation of data from archives, maps and reports, followed by field investigations of the hydrogeology and the soil. The groundwater levels were measured in 40 wells and tubes during spring, summer and autumn in 2002. The groundwater was sampled in the wells of the water supply during two periods (1999-2000 and 2002) for analysis of chloride, heavy metals (As, Cd, Pb and Zn) and lead isotopes. In 2002 the well no 3 (W3) was sampled once a month in spring, summer and autumn. The well no 2 (W2) was sampled in the spring and summer, however it was not possible to continue the sampling in that well from August and therefore well no 4 (W4) was sampled August-October. The two wells W2 and W4 have very similar groundwater chemistry. Groundwater from a tube in connection to the dumping site for the glass slag was also sampled a few times in 2002. The soil was sampled along the highway at different depth, in the dumping site in the surface layer and at 1.5 m depth and in the surface layer of a forest. The soil samples were analysed for Pb. Both groundwater and soil samples were analysed for Pb isotopes in order to separate the sources (Åberg 2001).

RESULTS

Hydrogeology

The area has a very flat topography and the hard rock is covered by a thin (0.5-5.0m) layer of gravelly till, which is fairly permeable and mostly in good hydraulic contact with the superficially fragmented rock (0-10m). Further down the porphyry rock is less fractured with extent of some zones. The recharge of groundwater is calculated to maximum 250 mm/y. A map of the water table shows that the groundwater in general flows in E or SE direction but a deep cone of depression is formed around two of the wells W2 and W4, which are located very close to each other. There is a very diffuse cone around the third well W3 and a moderate cone around the well of the glasswork in the north. The wells W2 and W4 have about the same capacity (short test pumping 3000 L/h). The third well W3 has the highest capacity (10,800 L/h). The well of the glasswork has a capacity of 6000 L/h and produces water for the industrial production.

Groundwater chemistry

The wells W2 and W4 have a similar water quality (neutral water with medium hardness, an alkalinity of 60 mg HCO_3/L) while the well W3 has a more acid water (pH 5.6-6.5) and lower alkalinity (15mg HCO_3 mg/L). The chloride concentration is lower in the wells W2 and W4 and less variable (in the range 20 mg/L to 50 mg/L) compared to well W3. The water chemistry of well W3 suggests a shallow groundwater with lower alkalinity and pH as well as the presence of bacterial pollution. The bacteria pollution was found to be related to leakage of waste water from some nearby private sewage system. The problem was solved by technical measures at the water work.

Well W3 frequently reach Cl concentrations of 80 to 150 mg/L and very occasionally 405 mg/L. A high concentration of chloride might have different sources: de-icing salt from roads, recent or relict sea water, waste water and very deep groundwater. As the area is situated far from the sea and high above the highest fossil shore-line, sea water can be eliminated as a source as well as very deep groundwater due to the moderate depths of the wells (80-100 m). Waste water may give an increased base-level but not the high peaks as in this case. The source of chloride is strongly correlated to the road salting with a delay of the groundwater recharge during the snow melting to roughly half a year. The infiltration spots are probable the road ditches blasted in the fragmented porphyry rock.

Heavy metals in the groundwater

The Pb concentration increased in the summer-autumn period and was close to the limit for drinking water quality (10 g/L) in well W3 (Fig.1). The Pb concentration is generally higher in well W3 than in the wells W2 and W4. However, the highest observed Pb concentration, 25 µg/L, has been measured in the well W2. However, the concentration in the drinking water distributed to the consumer has been low at all occasions with raised Pb concentration due to treatment in the waterworks.

There was also one exception from the general trend in 2002 with different heavy metal concentrations in the wells. In August, the concentration increases for Cd, Pb and Zn and became similar for the wells W3 and W4. The similarity at this occasion indicates that the there is the same water in the wells at this specific sampling occasion. The same trend was not at all present for As. Cadmium, Pb and Zn may all be related to road traffic but could also be related to the production of crystal glass. Arsenic on the other hand is more specific related to the production of crystal glass.

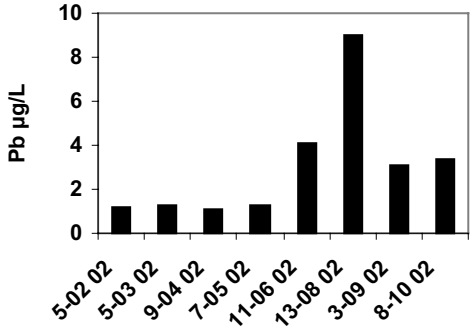

Figure 1. Lead concentration in well 3 (W3) during 2002. The limit for drinking water quality is 10 µg/L

Besides the natural enrichment of Pb in the till there is also one for Zn in a near-by area and accordingly none of the sources could be excluded. On the other hand, groundwater flow-lines showed that there is no groundwater flow from the dumping site for glass slag to the well field. However, the groundwater flow might be more complicated if fractured zones are included in the flow.

Lead isotopes

The $^{206}Pb/^{207}Pb$ ratios were very similar in the soil sample from the highway and the dumping site for glass slag, around 1.12-1.13 (fig.2).

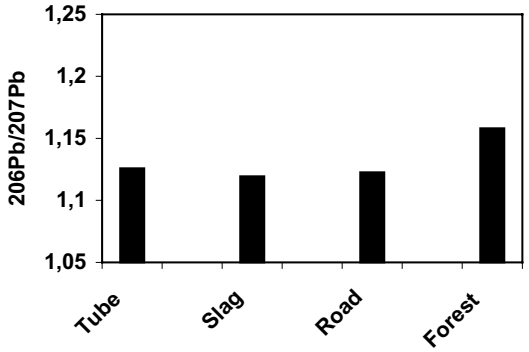

Figure 2. The $^{206}Pb/^{207}Pb$ ratios from the groundwater tube in connection to the dumping site and the soil in the dumping site, the road and forest surface layer

A similar value was also found in the groundwater in connection to the dumping site. In forest soil surface layer the ratio was 1.15 that is the frequently reported value in Sweden for soil surface layers affected by long-distance transported aerosols. Conversely, the ratios in the groundwater from the water supply had higher ratios than the two present possible sources for the high Pb concentrations, around 1.17-1.22. When the Pb concentration increases in August 2002, the ratio $^{206}Pb/^{207}Pb$ decrease (Fig.3). This suggests that there are different water in the wells at different sampling occasions. In August the groundwater level was also lower than at the other sampling occasions and deeper groundwater, possible transported in fractured zones, could be of importance.

The $^{206}Pb/^{207}Pb$ ratio in the Galena in a near-by area has also a low value (Sundblad 1997). A possible source for higher ratios is a natural enrichment of Pb in K-feldspar with ratios in the range 1.026 to 2.082 (K. Sundblad, personal communication). A possible scenario is that Pb has been weathered from the feldspar and precipitated as sulphides in the soil.

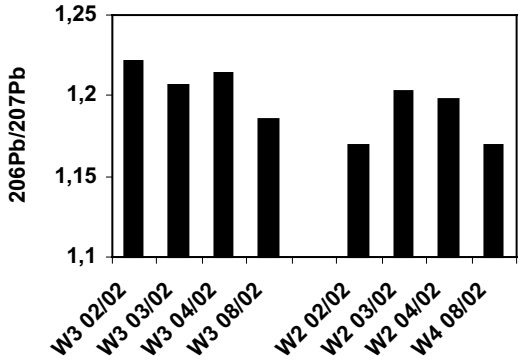

Figure 3. The ratio $^{206}Pb/^{207}Pb$ in groundwater from the waterworks. Wells nos 3 (W3), 2 (W2) and 4 (W4)

Since the isotope ratio from the third source is unknown it is not possible to define the contribution from each source. The usual ratio of around 1.2 in the water supply might be a result of one specific source with that ratio or more likely, a mixture of different sources. If the groundwater is a mixture of different sources, the lower ratio in August and higher Pb concentration could be explained by a different dominating source when the groundwater level is lower in summer-early autumn. This source might be of anthropogenic and/or natural origin since the isotopes in soil along the road, in the dumping site and in the Galena from the near-by area all have low Pb isotopes ratios.

REFERENCES

Åberg G (2001) Tracing pollution and its sources with isotopes. Water, Air and Soil Poll. 130:1577-1582

Norrström AC, Bergstedt E (2001) The impact of road de-icing salts (NaCl) on colloid dispersion and base cation pools in roadside soils. Water, Air and Soil Poll 127:281-299

SGU 1992 SGU, 1992 Soil Geochemical map 3-7, F-H Report no 73 (In Swedish)

Sundblad K (1997) Syngenetic Pb-Zn-Cu sulphide mineralization in 1.8 Ga subaerial volcanic rocks, southeastern Sweden. GFF 119:103-108

Numerical groundwater modelling in fractured environment: a planning tool for uranium mining remediation (Ronneburg site - Eastern Thuringia, Germany)

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A b s t r a c t : Uranium mining in the Ronneburg district, the largest of WISMUT's mine sites, started in 1951 and ceased in 1990. As an important part of WISMUT's remediation activities the mine is in the process of flooding since 1997. Before that groundwater drawdown covered an area of about 70 square kilometers. Steady-state and transient hydraulic simulations were the main tasks of the early years of modelling for the development of the flooding concept. The combination of hydraulic and geochemical models is typical for the present applications, which are necessary for the prediction of the impact of the flooding process to groundwater resources and surface waters. According to the quantitative model results the flooding operation is expected to complete between 2004 and 2005 after reaching a quasi-steady state of inundation. Another main task for present modelling activities is to attend the technical planning process of catchment systems for the controlled exfiltration of contaminated groundwater.

INTRODUCTION, GEOLOGY AND MINING ACTIVITIES

Uranium mining in the Ronneburg mining district (Eastern Thuringia), the largest of WISMUT's underground mine sites, started in 1951 and ceased in 1990. The deposit was situated in a series of blackshales, limestones and magmatites of Ordovician to Devonian age (Lange and Freyhoff 1991). By the end of 1990 the complex underground mine consisted of 14 mine fields with 40 shafts and about 3000 km of mine workings (see Fig.1). The Ronneburg mine accounted for about 50 percent of WISMUT's total uranium production of about 230.000 tonnes.

The mine levels were numbered according to their vertical distance to the surface. The main activities were concentrated between the 120-m- and the 390-m-level. The overall volume of the mine workings at the Ronneburg site amounted to about 68 million m^3 of which about 44 million m^3 were backfilled mainly with a special flyash cement as a characteristic feature of the cut and fill mining technology performed at Ronneburg since the late 1960s. About 4 million m^3 arose from caving which was practiced in the early mining period of the 1950s and 1960s.

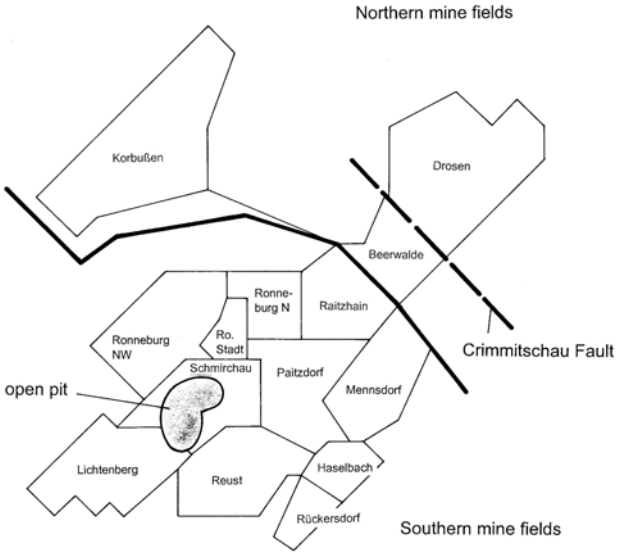

Figure 1. Schematics of the Ronneburg mine site showing the different mine fields

The mine fields of Beerwalde and Drosen are separated by the Crimmitschau fault, a supraregional fault zone. Mine workings which connected both mine fields had been backfilled prior to flooding. In contrast to the rest of the mine site at the Drosen mine field the palaeozoic host rock is covered by a series of platform sediments of Permian to Triassic age. In addition to the underground mine workings the investigations also had to consider the Lichtenberg open pit (see Fig.1) with an area of about 2 square kilometers and a depth of more than 240 meters. The open pit is in the process of backfilling with waste rock since 1991. The relocation of the piles and backfilling of the open pit are planned to be finished in 2007.

Fully-fledged flooding of the southern mine fields was initiated at the turn of 1997/1998 after a four-year-permitting and preparation process. Flooding of the northern mine fields started in 2000 (Paul *et al.* 1998, 2002, Gatzweiler *et al.* 2002).

HYDROGEOLOGY

Groundwater drawdown covered an area of about 70 square kilometers. Before flooding the average inflow into the southern mine fields amounted to about 650 m^3/h with variations from about 500 m^3/h up to 800 m^3/h (based on monthly values, time series between 1991 and 1999).

Monitoring data of the flooding process confirm the significant water quality differences between the various mine fields. Most contaminated waters are concentrated in the mine fields of Schmirchau and Lichtenberg. Mixing and horizontal flow in the course of flooding lead to variations in the water quality of some of the monitoring wells over time.

In terms of water quality conditions it has to be mentioned that at Ronneburg a very serious acid mine drainage problem exists. During active mining the mine waters were characterized by acid to neutral pH and high concentrations of radionuclides, heavy metals, iron, sulphate, and magnesium.

METHODS AND INVESTIGATIONS

Groundwater modelling was of crucial importance for the development of the flooding concept. Several modelling tools were implemented for the simulation of the flooding process over time, for the prediction of the final groundwater regime or to support the water management during the final flooding phases. As a speciality of the approach the simulation of the regional water balance had to be combined with the simulation of the situation in the mining excavations.

Steady-state and transient hydraulic simulations were the main tasks of the early years of modelling in the mid 1990's. The combination of hydraulic and geochemical models is typical for the present applications which are necessary for the prediction of the impact of flooding process to groundwater resources and surface waters.

Meanwhile groundwater simulation development and application activities have brought some experience in modelling the fractured environment of

- the paleozoical layers in the southern and northern mine fields
- the permotriassic layers in the Drosen mine field
- hydraulic shorts over a large distance by underground drifts.

The flow-model is the first step to get information on the contamination potential. The combination of a porous media and a hybrid model to consider hydraulic shorts (drifts, fractures) gave the possibility to calculate realistic scenarios of groundwater flow, since within the mining area the flow over such discrete elements is absolutely predominant.

For the purpose of water quality predictions PhreeqC was used. The multi-migrant transport process to calculate the pH- and Eh-value for the prognosis of the uranium and heavy metal future development is a special emphasis of the transport model.

The more important step, however, is the modelling of the mass transport. This mass transport model considers convection, diffusion/dispersion and retardation. The critical part of the approach is the source-sink-term. A lot of investigations were performed at WISMUT to develop realistic source-sink-terms.

RESULTS AND DISCUSSION

As a central result of the simulation the prognostic description of the

- quantitative and
- qualitative

characteristics of groundwater exfiltration in the final phase of the flooding process has been realised. According to the quantitative prognostic modelling results the flooding operation is expected to complete between 2004 and 2005 after reaching a quasi-steady state inundation level of about 265-285 m a.s.l. which is important for the layout of the decommissioning regime at the Ronneburg site. Results of mass-transport calculations are for instance concentration vs. time plots at certain control points.

Since there are no open dewatering tunnels within the whole mining field flooding would continue until the natural discharge of the contaminated groundwater to the local receiving streams if no active pumping or collection measures are carried out. Because of the degree of contamination of the mine waters active water treatment proved to be necessary. Contaminants of concern are the radionuclides, various heavy metals, iron and arsenic, but also sulfate and hardness. So water catchment systems have to be installed close to the surface within areas with a high probability for exfiltration of contaminated groundwaters into the receiving streams.

Local groundwater models are important tools in to support that process. Furthermore consideration of the numerous creeks and streams with expected exfiltration conditions in the final phase of the flooding process has crucial importance in the present model investigation activities. This also includes the simulation of technical water catchment systems as a boundary condition for the combined fractured/ porous groundwater system in the Ronneburg region.

A main task for present modelling activities is to attend the technical planning process of catchment systems for the controlled exfiltration of contaminated groundwater (Unland *et al*. 2002). These include the identification of the locality and furthermore the hydraulic and hydrochemical characteristics of the exfiltration processes. These results are also important for the technical planning of water transport and water treatment facilities.

ACKNOWLEDGEMENT

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REFERENCES

Gatzweiler R, Jakubick AT, Paul M, Schreyer J, Meyer J (2002) Flooding the WISMUT mines - Learning by doing or applying a comprehensive systematic approach?- Uranium in the Aquatic Environment.- In: Proceedings of the International Conference Uranium Mining and Hydrogeology III and the International Mine Water Association Symposium Freiberg, Germany, 15-21 September 2002, Springer 2002, pp 745-754

Lange G, Freyhoff G (1991) Geologie und Bergbau in der Uranlagerstätte Ronneburg/ Thüringen.- Erzmetall 44:264-269

Paul M, Sänger HJ, Snagowski S, Märten H, Eckart M (1998) Flutungsprognose am Standort Ronneburg - Ergebnisse eines integrierten Modellansatzes.- Uranium Mining and Hydrogeology II, Proceedings of the International Conference and Workshop, Freiberg, Germany, September 1998. GeoCongress 5, Verlag S v Loga, 130-139

Paul M, Gengnagel M, Vogel D, Kuhn W (2002) Four years of flooding WISMUT's Ronneburg uranium mine - a status report. In: Uranium in the Aquatic Environment. Proceedings of the International Conference Uranium Mining and Hydrogeology III and the International Mine Water Association Symposium Freiberg, Germany, 15-21 September 2002, Springer 2002, pp 775-784

Unland W, Eckart M, Paul M, Kuhn W, Ostermann R (2002) Groundwater rebound compatible with the aquatic environment – technical solutions at WISMUT's Ronneburg mine. In: Uranium in the Aquatic Environment. Proceedings of the International Conference Uranium Mining and Hydrogeology III and the International Mine Water Association Symposium Freiberg, Germany, 15-21 September 2002, Springer 2002, pp 667-676

Groundwater pollution assessment using discriminant variables

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A b s t r a c t : Hydrogeological investigation in hard rocks of Mirandela region (NE Portugal) led to the definition of two different hydrogeological units: Igneous Unit (UI) and Metamorphic Unit (UM). The first one is characterised by a median conductivity of 88 μS/cm while the second shows a higher median value of 253 μS/cm. The typical hydrochemical facies in UI is sodium bicarbonate and in UM is calcium bicarbonate. A correspondence analysis was made using chemical variables, as well as other variables in a classificative scale, such as lithology and presence of faecal coliformes. The results indicate that three main factors determine water characteristics: a lithological factor and two factors related with anthropogenic processes (agriculture practices and domestic effluents). In order to establish an easy method to identify contaminated samples, the chloride and bicarbonate concentrations were compared. Two different trends were defined which allow to distinguish polluted from unpolluted groundwater.

INTRODUCTION

With the purpose of making the hydrogeological study of Mirandela region, NE of Portugal, Pereira (1999) developed several studies such us the hydrogeochemical characterisation.

For such purpose physical, chemical and bacteriological data from 45 water samples, collected in springs and wells from fractured igneous and metamorphic rocks were used.

These data were analysed with a factorial analysis of correspondence to define the main factors that determine water characteristics.

Based on these results we are trying to define if there´s some discriminant variables in groundwater pollution assesment.

HYDROGEOLOGICAL SETTING

The region is separated from the coast by the presence of two mountainous ridges, which prevent the ocean influence giving a continental character to the climate.

The mean annual precipitation ranges from 500 mm/year to 1300 mm/year and the mean annual temperature between 10 ºC and 14 ºC.

The geology of the area is rather homogeneous and is dominated by Palaeozoic schists and quartzites from hercynian schield in NW of Iberian Meseta. In the northern part of the area some hercynian granites are present.

Two different units were defined (Fig.1):

- Igneous Unit (which includes two mica granites) - characterised by a median conductivity of 88 μS/cm, sodium bicarbonate facies, and yields 0.2 L/s in average;

- Metamorphic Unit (which includes schists and quartzites) - with a higher median conductivity (253 μS/cm), calcium bicarbonate facies and higher yields (1.5 L/s in average) (Pereira and Almeida 1997).

Geochemical modelling results show that the most frequent water-rock interaction are the dissolution of plagioclase and biotite, or chlorite, which induce the precipitation of clay minerals, usually kaolinite (Pereira and Almeida 2000). In some metamorphic rocks carbonate minerals (calcite) are present in cement. In those cases the mineralization of water samples is higher and attributed to the easy dissolution of carbonates.

DATA ANALYSIS

A correspondence analysis was made using chemical variables, as well as other variables in a classificative scale such as presence or absence of faecal coliforms.

Figure 1. Hydrogeological Units of study area

The results of the correspondence analysis led to the definition of three main factors that determine water characteristics: a lithological factor, that explains 33.6% of variance and allows to clearly separate groundwaters from Igneous Unit from those of the Metamorphic Unit, and two factors related with anthropogenic processes (agriculture and domestic effluents), that explains 21.4 and 13% of variance respectively.

The main impact on groundwater from agricultural activities is due to the usage of inorganic fertilisers and manure. The last type is responsible by the increase of several species including chloride, nitrate and bicarbonate.

The bicarbonate ion increase is due to the production of CO_2, by organic matter decay, which induces silicate weathering. Another consequence of agricultural activities may be a general increase in dissolved salts due to recycling of water by irrigation.

Domestic effluents are responsible by increasing content in chloride, nitrate and by the presence of faecal coliformes.

BICARBONATE/CHLORIDE RELATION AS A CONTAMINATION INDICATOR

In this geological environment chloride ion is a conservative component whereas the bicarbonate ion is mainly related with water-rock interaction.

Correspondence analysis show that chloride ion is related with anthropogenic contamination (either agricultural or domestic).

In order to establish an easy method to previously identify contaminated water samples, the chloride and bicarbonate concentrations were compared.

Fig.2 shows two main trends in the evolution of groundwater composition:

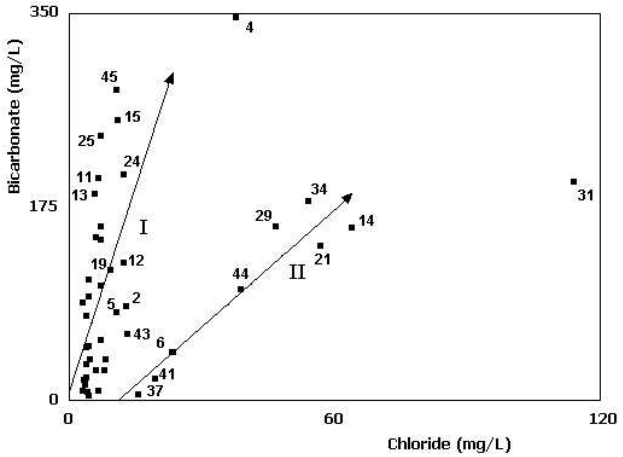

Figure 2. Variation of Chloride (Chl) and Bicarbonate (Bic) concentration in groundwater from igneous and metamorphic rocks (NE Portugal)

I - Evolution of Bic/Chl by water-rock interactions
II - Evolution of Bic/Chl afected by contamination

The group I is characterised by natural processes of water-rock interaction without evident anthropogenic influence. The increase in bicarbonate content indicates higher geochemical evolution. The chloride content is always lower than 15mg/L.

There is a weak relationship between the two variables:

$$Bic = 12.35\ Chl - 8.59;\ r = 0.493 \qquad (1)$$

The regression of chloride over bicarbonate (1) show that the increase of the former with rock weathering is only 0.03 mole by each mole of bicarbonate.

The group II corresponds to contaminated samples showing a high correlation between bicarbonate (Bic) and chloride (Chl). The regression equation for group II is:

$$Bic = 3.5\ Chl - 39.8\ ;\ r = 0.946 \qquad (2)$$

Inside this group a separation can be made between waters associated with igneous rocks (with lower mineralization) - samples 37, 41 e 6 -, but with the same evolutionary trend, and the remaining samples of this group - 44, 29, 21, 14, 34 e 31. These last ones are associated with metamorphic rocks.

As it was said before total mineralization is smaller in igneous rocks, were the principal dissolved minerals are silicates. On other hand the presence of small quantities of carbonates in rock cement of some Palaeozoic schists explains the higher conductivity of groundwater from this litologies.

Sample 4 diverge from any of the presented groups due to local geological context were the presence of sulphide mineralization in quartz veins is responsible for pyrite oxidation reactions. The oxidation of sulphide minerals gives a high concentration in dissolved sulphate in water composition and the H^+ ions release during oxidation promote the dissolution of silicate minerals and gives a very high conductivity of the groundwater (about 1000 μS/cm).

CONCLUSIONS

In the studied area the chloride content in water samples is a good discriminant variable for detecting agricultural and domestic contamination of groundwater.

In water samples not influenced by anthropogenic factors the chloride content is always below 15 mg/L and is weakly related with the bicarbonate ion, whereas in contaminated samples the chloride content is higher than 15 mg/L and shows a good relationship with bicarbonate. The regression equation (2) between the two variables – bicarbonate and chloride - for contaminated samples, is defined by: Bic = 3.5 Chl - 39.8 , with a correspondence coefficient of 0.946.

This is due to some underlying process responsible by the increase of both species. We think that the bicarbonate ion increase is due to the production of CO_2, by organic matter decay, which induces silicate weathering. The organic matter, as well as chloride, is present in urban effluents and in manure used as fertiliser.

REFERENCES

Pereira MR. (1999) Hidrogeologia das Rochas Fracturadas da Terra Quente Transmontana. PHD in Univ. de Trás-os-Montes e Alto Douro, 299 pp

Pereira MªR, Almeida C (1997) Influência da Posição Topográfica e da Litologia na Produtividade das Captações em Rochas Fracturadas de Trás-os-Montes Oriental (Portugal). In: Workshop of Iberian Subgroup on Hard Rock Hydrogeology Proceedings, pp 67-78

Pereira MªR, Almeida C (2000) Geochemical evolution of groundwater in metamorphic rocks of Trás-os-Montes (Portugal). In: Oliver Sililo *et al.* (eds) Groundwater: Past Achievements and future challenges, pp 587-591

Hydraulic characterization of karst structures and water-containing fractures in deep underground excavations

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A b s t r a c t : Many tunnels that are currently being built through the Alps have to cross fractured and karstified formations at great depth and many hundreds of meters below the ground water table. The detection and characterization of permeable structures ahead of the advancing tunnel face is vital for these projects. We present new prediction and analysis methods and actual results from a deep Alpine tunnel in Switzerland, which has recently crossed 3.5 kilometres of karstified and fractured limestones under an overburden of 1000 meters (Fig. 1). The exploration programme in this part of the tunnel was unique and includes about 10‘000 m of cored boreholes tested systematically with open hole and packer tests. From the high resolution transient pressure records of these experiments we derived not only standard hydraulic formation properties but also diagnostic information including type, orientation and dimension of permeable structures. The subsequent tunnel excavation at the test locations allowed to directly map the permeable structures and to evaluate the diagnostic model results.

Karstification of limestones and dolomites can lead to various types of solution voids, among which many can lead to preferential pathways with very large hydraulic conductance. An underground excavation intersecting such structures in the saturated part of an aquifer, can be confronted with extreme water inflows. Besides the karst structures water containing fractures with high hydraulic transmissivities can cause great problems during tunnel excavation especially if these fractures are hydraulically connected to karstified structures or even Quarternary gravel fillings of valleys at greater distance. Many tunnels that are currently being built through the Alps have to cross such formations at great depth and many hundreds of meters below the regional ground water table. Therefore, the detection and characterization of karstified zones, karst pipes and water-containing fractures ahead of the advancing tunnel face is vital for these projects. We present new prediction and analysis methods and actual results from a deep Alpine tunnel in Switzerland, the double tube Lötschberg Base Tunnel (LBT) of the Swiss AlpTransit Project, which has recently crossed 3.5 kilometres of limestones (karstiefied and fractured) under an overburden of up to 1000 meters (Fig.1). The main focus of this paper are the possibilites and limitations of systematic hydraulic measurements performed in nearly horizontal 100 to 400 m long exploration boreholes drilled from the tunnel face during tunnel driving.

Within the marl sections of the so-called Doldenhorn nappe exploration during tunnel driving consisted of 1 horizontal cored borehole per tunnel tube. In the potentially karstified limestone sections the exploration included at least two boreholes per tube including hydraulic open hole and packer tests as well as systematic borehole radar measurements. Depending on the results of these first boreholes, drilling and testing was subsequently increased in zones showing indications for karstification and fracturing. Strongly karstified or fractured sections were tested with at least 4 nearly parallel core boreholes before any decision regarding continuation of tunnel driving or injection was taken. During the exploration programme in the Doldenhorn nappe with a length off approx. 3.5 km, 41 cored borholes and 10 destructive horizontal boreholes were drilled. Transient open hole and packer based hydraulic tests were systematically performed in most of the horizontal exploration boreholes. Due to the hydrogeological conditions (very few permeable features intersected far away from the borehole head) and the carefully cemented 20 m long stand pipes, both methods gave nearly the same results. The test sequences included constant rate, constant head and pressure build up phases which were recorded in the active borehole as well as in observation boreholes. The time span of an open-hole test was between 30 and 80 min for the drawdown phase and 40 to 120 min for the pressure recovery phase. Pressure was recorded with a high

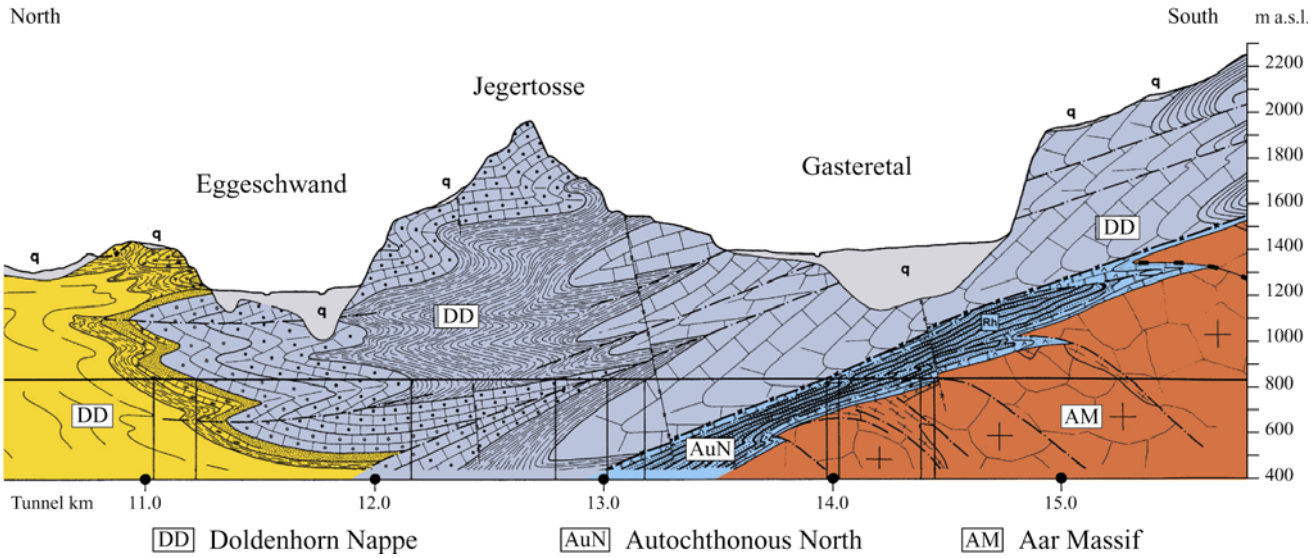

Figure 1. Cross section of the Doldenhorn Nappe in the Lötschberg Base Tunnel. The karstified and fractured Zone is indicated as “DD“ and coloured in blue

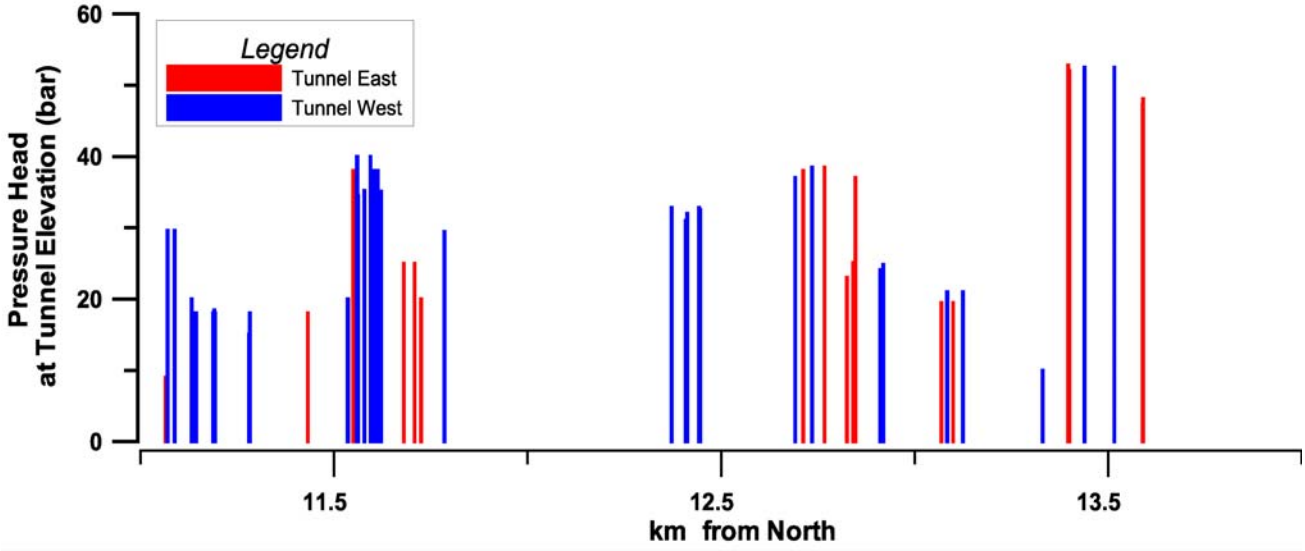

Figure 2. Formation pressure head measured along the Lötschberg Base Tunnel in the section of the Doldenhorn nappe. The distribution of pressure heads does not correspond to the overburden and shows indications of pressure compartments

resolution pressure sensor and digital datalogger in an interval of 1 second.

Single and crosshole responses gave extremely powerful results regarding local and far field hydraulic transmissivity, lateral extension and connectivity of permeable features, pressure head, storativity and drainable water volumes. Most of the vital decisions regarding continuation of tunnel excavation or time consuming sealing actions were based successfully on this data set.

In addition to these practically important findings, the hydraulic responses measured during longer-term constant rate outflow tests were used to evaluate pressure compartmentalisation (Fig.2) and to systematically analyze diagnostic plots (Fig.3). These plots showed pressure responses with very characteristic patterns, e.g. radial flow or bilinear flow which is typical for planar finite conductivity fractures having a similar strike direction like the horizontal boreholes. Other flow tests showed responses which can not easily be explained with classical models from (surface based) borehole tests. The subsequent tunnel excavations at the locations of these tests will be used to directly map the tested permeable structures and to evaluate the diagnostic model results.

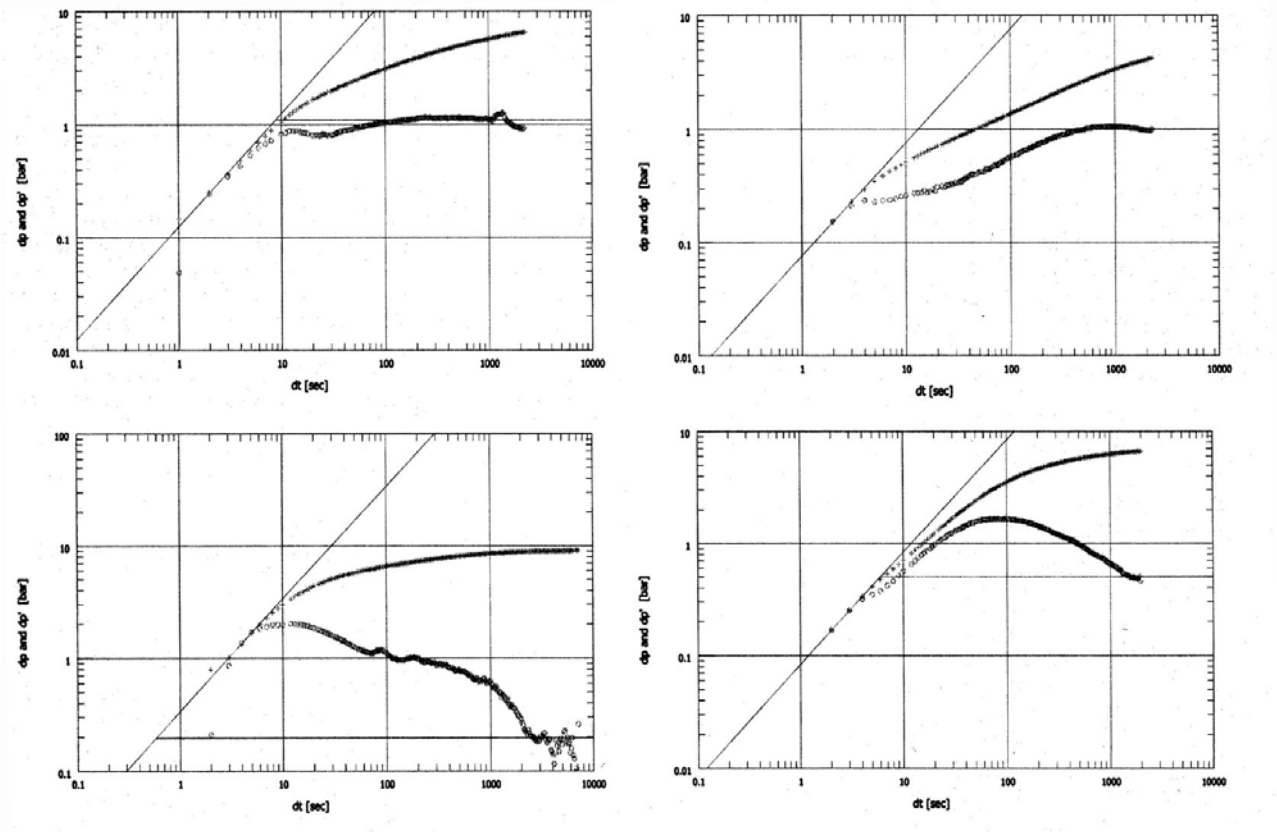

Figure 3. Examples of diagnostic plots of observation well responses to constant rate outflow tests in open boreholes drilled from the tunnel face into the limestones of the Doldenhorn nappe

Delineation of groundwater protection zones in fractured media: presentation of a new systematic methodological approach

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A b s t r a c t : A new methodological approach is proposed for the delineation of groundwater protection zones in fractured media. It takes into account the diversity of geological and hydrogeological conditions prevailing in fractured aquifers in Switzerland and provides appropriate solution for the different types of settings observed. Three different methods are used, depending on the vulnerability of the catchment facility and the heterogeneity of the aquifer.

INTRODUCTION

Under the Swiss Water Protection Ordinance of 28 October 1998, the degree of vulnerability in the catchment area of springs and wells determines, in fractured media, the delineation of groundwater protection zones. A new methodological approach is proposed (Pochon and Zwahlen 2003) to facilitate the application of this ordinance.

Due to the presence of various types of hydrogeological settings in Switzerland, it is not possible to delineate protection zones according to a uniform method in fractured media. It was thus necessary to develop a new methodological approach first allowing selection of the right method and then application of the appropriate procedure for delineation of protection zone in each case (fig.1).

METHODOLOGICAL APPROACH

Basic data, evaluation of the catchment facility vulnerability

The first step includes the collection and the interpretation of basic data concerning the aquifer and requires an adequate monitoring of the catchment facility (spring, well). Monitoring of discharge, physico-chemical parameters, turbidity and biology, including observations in various hydrological conditions, allow global vulnerability of the catchment to be evaluated. If the vulnerability is low, protection zones can be defined with a minimum size (Distance Method). For vulnerable catchments additional investigations are needed.

Additional investigations, evaluation of aquifer heterogeneity

The required additional investigations include a more detailed analysis of fracturation in the water catchment area and tracer testing. It allows gaining more precise information concerning groundwater flow behaviour and the degree of aquifer heterogeneity. If the catchment is vulnerable and the degree of heterogeneity is found to be low, the protection zones are delineated by means of isochrones (Isochrone Method) on the basis of tracer testing. If the catchment is vulnerable and the aquifer is highly heterogeneous, a multi-criteria groundwater vulnerability mapping method is applied (“ DISCO” Method).

DELINEATION OF PROTECTION ZONES, EXAMPLES

Development of the methodology was based on observation of several test sites representative of the diversity of geological and hydrogeological settings in Switzerland. Three selected examples illustrate the application of the different methods.

Distance method, Sarreyer test site

The Sarreyer test site is located in the western part of the Swiss Alps. The aquifer consists of metamorphic gneiss and schist. The catchment work collects water from four 20 to 30 meters long sub-horizontal boreholes. Water quality is perfect throughout the year and no significant variation of discharge, conductivity or quality is observed even during heavy rainfall. This accounts for a low vulnerability of the catchment facility.

In such a setting, no additional investigations are needed. The delineation of protection zones of minimal extension according to the Swiss Ordinance (100 meters between the outer limits of S1 and S2 zones) is sufficient to preserve the quality of water.

Isochrones method, Ronco sopra Ascona test site

The second test site is situated in the southern part of the Swiss Alps. The aquifer is build of metamorphic amphibolites and gabbros. The catchment work collects water directly from a fracture. Significant variations of discharge, conductivity and temperature are observed during the year and suggest that the catchment facility is potentially vulnerable to contamination.

Additional investigations concerning structural geology, geomorphology and multi-tracer experiment led to the conclusion that the aquifer was weakly heterogeneous and that the application of the isochrone method was required in this case.

Based on the maximum velocities determined by tracer experiment (15 m/day), outer limit of S2 corresponding to the isochrone of 10 days according to Swiss Ordinance was fixed at a distance of 150 meters from the catchment work.

“DISCO” method, Rieden test site

The Rieden test site is located in the eastern part of the Sub-Alpine Molasse. Sandstones, conglomerates and marls constitute the aquifer. The two catchment works of interest collect directly the water from fractures in sandstones and conglomerates. Data concerning discharge, physico-chemical parameters, turbidity and bacteriology show frequent quality problems, which prove that catchment facilities are particularly vulnerable to contamination.

Additional investigation revealed the presence of point infiltration, sinking streams and important phenomena of dissolution and subrosion. Groundwater flow velocities up to 1 kilometer per day were measured during tracing test experiments and demonstrated the presence of vulnerable zones distributed in the whole catchment area of the two springs.

The DISCO method was thus applied, including four steps as follows (fig.1): 1) evaluation and mapping of the parameters discontinuities and protective cover on the whole catchment area of the spring, 2) processing of the intermediate protection factor

map F_{int} by combining these two parameters, 3) in case of significant run-off processes, partial adjustment of the current map by taking into account potential surface flow of pollutant towards the most vulnerable area, 4) delineation of protection zones based on the final protection factor map.

CONCLUSION

This new methodological approach for the delineation of protection zones in fractured media was tested in various hydrogeological settings in Switzerland and proved to give appropriate results. Additional advantage to propose a more detailed or a less detailed study depending on the global vulnerability of the catchment facility and on the heterogeneity of the aquifer is also to keep costs low for the simple cases and to require more detailed and expensive studies only for the more problematic cases.

REFERENCES

Pochon A, Zwahlen F (2003) Délimitation des zones de protection des eaux souterrraines en milieu fissuré. Guide pratique. OFEFP/OFEG, Berne, 84 pp.

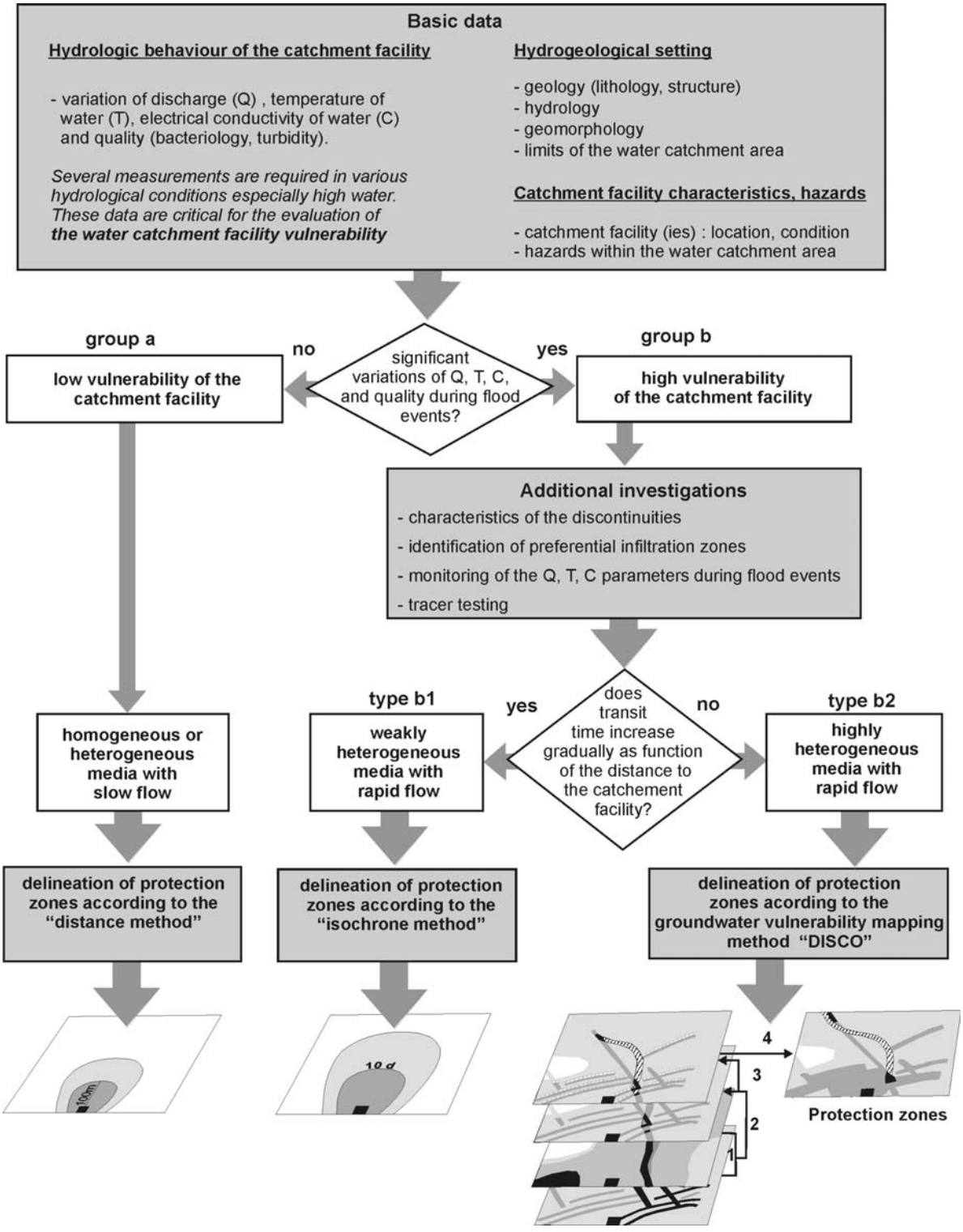
Basic data
Hydrologic behaviour of the catchment facility
- variation of discharge (Q) , temperature of water (T), electrical conductivity of water (C) and quality (bacteriology, turbidity).
Several measurements are required in various hydrological conditions especially high water. These data are critical for the evaluation of the water catchment facility vulnerability
Hydrogeological setting
- geology (lithology, structure)
- hydrology
- geomorphology
- limits of the water catchment area
Catchment facility characteristics, hazards
- catchment facility (ies) : location, condition
- hazards within the water catchment area
group a
low vulnerability of the catchment facility
no
significant variations of Q, T, C, and quality during flood events?
yes
group b
high vulnerability of the catchment facility
Additional investigations
- characteristics of the discontinuities
- identification of preferential infiltration zones
- monitoring of the Q, T, C parameters during flood events
- tracer testing
homogeneous or heterogeneous media with slow flow
type b1
weakly heterogeneous media with rapid flow
yes
does transit time increase gradually as function of the distance to the catchement facility?
no
type b2
highly heterogeneous media with rapid flow
delineation of protection zones according to the "distance method"
delineation of protection zones according to the "isochrone method"
delineation of protection zones acording to the groundwater vulnerability mapping method "DISCO"
100m
1 2 d
4
3
2
1
Protection zones

Figure 1. Methodological approach for delineating groundwater protection zones in fractured media

Temporary artificial drawdown of a joint aquifer: test design and methodology shown on a tunnelling project in an artesian spa-water aquifer, Tyrol, Austria

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A b s t r a c t : During excavation of the Brixlegg East Reconnaissance Tunnel, a fault zone containing unconsolidated rock and groundwater was discovered. Continued drainage was not possible because of possible detrimental effects on a nearby health spa and mineral water bottling facilities. A large-scale grouting programme failed to enhance rock stability. A drainage experiment was conducted to evaluate the impact of an artificial groundwater draw-down on the aquifer(s) in the area. An extensive above and below ground hydrological and geotechnical testing and monitoring programme was carried out. All measurements were entered in a data visualisation programme to compare measured values to previously defined criteria for discontinuing or adjusting the experiment. By using this dense observation network it was possible to locate the boundaries of the spa water aquifer and to assess the magnitude of impact. Based on these results further tunnelling is economically feasible if all relevant construction measures are carried out.

INTRODUCTION

In the course of the reconnaissance works, for the first construction stage of the Railway Project Munich - Verona, in the Lower Inn Valley, Austria, the Brixlegg East Reconnaissance Tunnel (planned length 2.5km) was excavated using the NATM (New Austrian Tunnelling Method). During drilling works for anchors, between tunnel metres 2268–2276 (Raibl Formation), massive ingresses of water occurred, containing sand- and gravel-like material. This zone, which the drillings penetrated, has a thickness of up to 30 m and contains groundwater under pressures of up to 5 bar. The zone was subsequently determined to be a fault zone made up of unconsolidated rock.

At the time, hydrological monitoring indicated a possible connection to a health spa, which is located at a distance of app. 600m from the site of the water ingresses. A detrimental effect on other mineral water bottling facilities, located 1.5km from tunnel metre 2268, could also not be excluded. Subsequently, a large-scale grouting programme was carried out to enhance the rock stability. However, it failed to provide the necessary grouting effect required to enable further tunnelling (Reichl *et. al.* 2002).

In view of the fact that further tunnelling would only be economically feasible at a reduced groundwater pressure, a sixteen-week drainage experiment was conducted to evaluate the impact of an artificial groundwater draw-down to the aquifer(s) in the area.

This experiment was aimed at providing the following information or allowing for the following exploration: (1) Extension of aquifer(s), (2) Magnitude of impact on the groundwater systems in the area, (3) Reversibility of the effects of an artificial draw-down, (4) Exploration of pressure distribution/conditions with respect to further tunnelling and (5) Geological exploration of the fault zone at reduced water pressures.

METHODOLOGY

For this experiment, an extensive above and below ground hydrological and geotechnical monitoring programme was planned (figs 1,2). Based on the existing geological and hydrogeological knowledge and estimated impacts, the points of measurement in the Brixlegg area were assigned to categories of different monitoring and sampling intensities. This classification was based on the expected magnitude of impact.

The main aspects of the hydrological and geotechnical monitoring programme were:

- Further controlled drillings in the reconnaissance tunnel which enabled the extraction of rock cores for geological analysis, the taking of water samples at defined points, geophysical measurements and packer profiling in the individual types of aquifer located in the fault zone (Fisch *et al.* 2003).
- The measurements were carried out manually, by continuous automatic data samplers, and by the automated data acquisition system GeoMonitor based on a network of physically interconnected sensors.
- Depending on the category of the point of measurement, and the type of measuring, the measuring rate varied from ten seconds to twice a day.
- During the experiment, a total of 50 000 manual measurements were taken in 99 days.
- The hydrological field parameters comprised groundwater level/flow-rate, electrical conductivity, temperature and water clarity. In addition, water samples were taken at least once a week and analysed for their chemical and isotopic ($\delta^{18}O$, ^{3}H, $\delta^{34}S$) content, and in some cases, for their bacteriological content.
- In order to detect any possible mass rock deformation, attributed to the groundwater draw-down, extensive above and below ground geodetic and geotechnical measurements were taken.

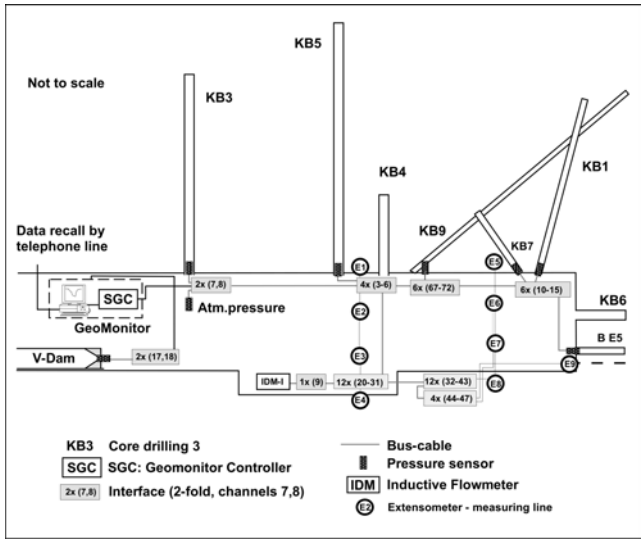

Figure 1. Configuration of the exploratory wells, extensometer and the GeoMonitor measuring system in the tunnel

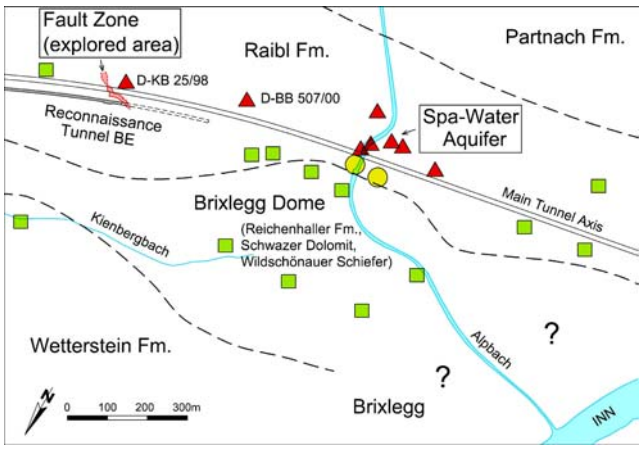

Figure 2. Configuration of the measurement points at the surface and their reactions (triangles = reaction water level/discharge, electric conductivity; circles = reaction electric conductivity, squares = no reaction)

The numerous automated and manual measurements were entered into a data visualisation programme (DAVIS), which facilitated a data review in their respective local and geographical context (fig.3).

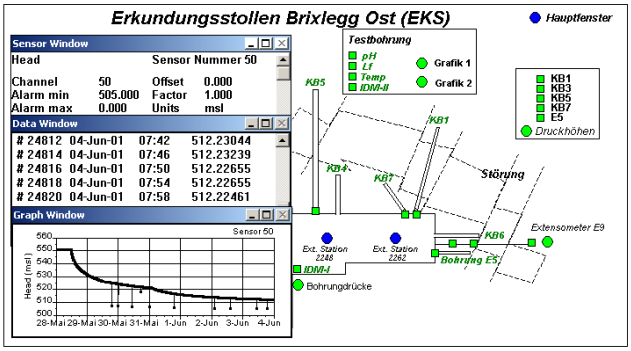

Figure 3. Example of visualised data using the programme DAVIS

By adopting this approach, it was possible at all times to compare the measured values to the previously defined criteria drawn up for discontinuing the experiment (fig.4).

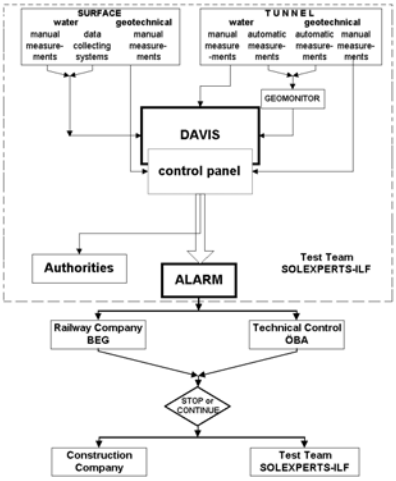

Figure 4. Schematic event and alarm plan

These criteria had been defined with a view to the stability of the tunnel and the quantitative and qualitative supply for the spa. The measured values were constantly monitored for criteria value violation. The Railway Company, the Technical Control and the authorities were kept informed about the state of the experiment (fig.4). For an overall interpretation of how well the experiment was running, a continuous interdisciplinary gathering of all the data from above and below ground took place (fig.5). The interpretation was then used to co-ordinate further detailed exploration during the experiment.

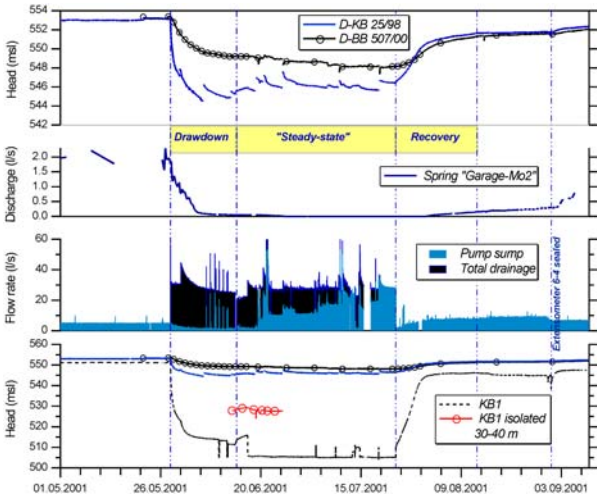

Figure 5. Overview of draw-down curves at selected below and above ground monitoring locations

RESULTS

A hydraulic connection was found between the water-saturated fault zone encountered in the exploratory tunnel, and the health spa, located at a distance of app. 600m (fig.2). A hydraulic connection to the mineral water resources located at a distance of 1.5km was definitely ruled out. Using data retrieved from this dense observation network, it was not only possible to locate the boundaries of this spa water aquifer, but it was also possible to assess the magnitude of impact.

The aquifer in question is a confined aquifer, laterally displaced in its longitudinal extension (Sausgruber, Brandner, in press). As a result of its high hydraulic conductivity, any changes in its water balance tend to affect the springs associated with it within a short time.

As soon as the groundwater level increased to normal, the flow-rate of the springs in most cases returned to normal. This showed that the impact of an artificial temporary draw-down of the aquifer, from within the exploratory tunnel, is reversible to a large extent.

Under these boundary conditions further tunnelling is economically feasible, if all the relevant supporting measures are carried out. These support measures must be such that the impact on the spa water aquifer is reduced to an acceptable minimum, and the use of its waters for a health spa is maintained.

REFERENCES

Reichl I, Wollmarker R, Stadler G, Schretter K, Eder S (2002) Erkundungsstollen Brixlegg Ost, Beispiel für die Grenzen der Wirksamkeit von Felsinjektionen. Proc. 17. Christian Veder Kolloquium, Graz, Austria, 177–192

Fisch HR, Mammel R, Poscher G, Reichl I (2003) Methods of fractured aquifer characterisation using an example of a brittle fault zone in calcareous rock. In: IAH International Conference on Groundwater in fractured rocks Prague, 15-19 September 2003 – Proc in prep

Sausgruber T, Brandner R (in press) The relevance of brittle fault zones in tunnel construction – Lower Inn Valley Feeder Line North of the Brenner Base Tunnel, Tyrol, Austria. Mitt der Österr Geol Ges 94, Vienna, Austria

Nitrate pollution in hardrock formations: vulnerability and risk evaluation by geomathematical methods in Serpa-Brinches aquifer, South Portugal

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A b s t r a c t : Public supply to Serpa, a major village of Alentejo region (South Portugal), depends partially on groundwater resources of a gabbro-dioritic aquifer corresponding to the east sector of the "Gabros de Beja" aquifer system. The study area (50 km^2) is located in the left margin of the Guadiana River, in the Ossa-Morena geotectonic unit. The shallow aquifer is developed in a 30 meters thick altered zone. Due to agricultural activities, the groundwater nitrate content often exceeds 50 mg NO_3/L. In order to evaluate the extension of this large-scale diffuse pollution a monitoring program was carried out between 1997 and 2000 to assess spatial and temporal variability of nitrate contents in the aquifer due to seasonal fertilization. Characterization of nitrate diffuse pollution was made by using various geomathematical techniques. A new type of susceptibility index was applied to the region to analyse the impact of the land agricultural uses on groundwater.

INTRODUCTION

The global increase of groundwater uptake is mainly due to the enlargement of irrigated zones. Although agricultural activities are one of the major consumers of groundwater they are also one of the main sources of groundwater pollution, because of inappropriate management and fertilizing practices. To support the planning and management of groundwater resources it's important to develop a multi-disciplinary methodological approach, that allows the determination of nitrate sensitive zones of the aquifer system and at the same time contribute to the improvement of the monitoring program.

METHODOLOGY

The characterization of the region in which the case study is integrated, was made after acquiring the necessary knowledge and data to perform this study. It was necessary to analyze proper geological and hydrogeological maps and reports. Aquifer recharge evaluation was estimated by using chloride mass-balance method. Hydrochemical characterization was performed by classical methods (Piper, Stiff) based on 53 water samples of 28 wells and by Principal Component Analysis (PCA) technique in two periods (high and low seasons) in order to describe the structural relationships between physical and chemical parameters, specially the detection of a relation between the nitrate concentration and other parameters. Groundwater flow simulation was performed for different climatic and exploration scenarios. Iso-probability maps of nitrate concentrations exceeding the specific threshold of 50 mg/L were produced using indicator geostatistic approach and vulnerability pollution maps were elaborated using a specific susceptibility index. These maps were made in a GIS environment.

HYDROGEOLOGY AND LAND USE

The study area belongs to the east sector of the "Gabros de Beja" aquifer system (Fig.1). The area is located on the left side of the Guadiana River and its extension is about 50 km^2. The study area is located in a wider region, between Ferreira do Alentejo (NW) and Serpa (SE) covering an area of about 350 km^2 in the Ossa-Morena geotectonic unit. It is composed mainly of two units: the Maphic and Ultramaphic Beja-Acebuches Complex and the Beja Gabbros Complex. In the Beja area predominant formations are gabbro-dioritic rocks. The altered zone varies locally, and it may reach 30 meters thickness creating an unconfined aquifer. The gabbro-dioritic aquifer is one of the most productive formations of the Alentejo region when comparing it with other fissured compact rocks, except karst systems. Transmissivity values may reach, in some areas, about 350 m^2/day and usually are between 50 and 100 m^2/day. In what concerns land use (remote sensing from 1987 Corine Land Cover), this sector is mainly occupied by agricultural activity (Fig.2) with 60.3% of covered area, where the main crops are wheat, sunflower, and permanent irrigated culture. Other areas of this sector have permanent cultures like Olive trees (21.5% of the total area) and agro-forest zones (12.8%).

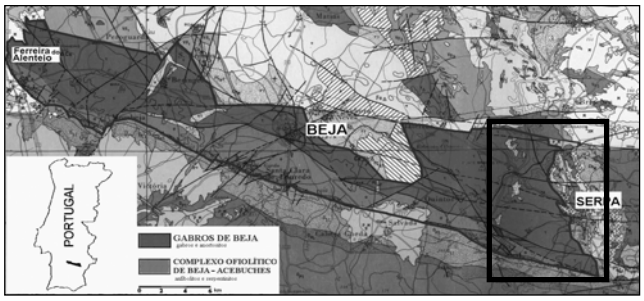

Figure 1. Geographical location of "Gabros de Beja" aquifer system (350 km2) and study area (50 km2).

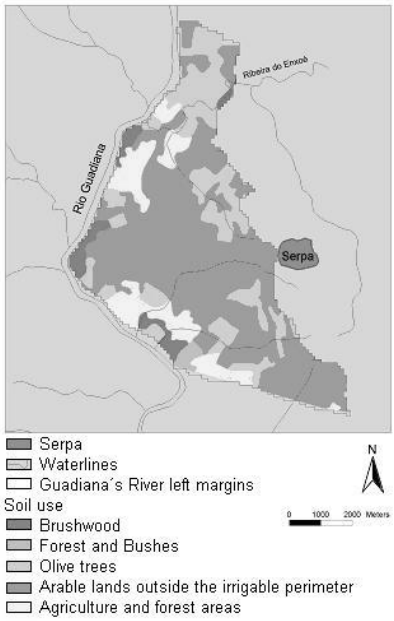

Figure 2. Land Use Map

RESULTS

A PCA was applied to a matrix of hydrochemical data (25 samples *versus* 9 variables) to investigate the main structural features between groups of variables. Results show that nitrate contributes with a high weight to the interpretation of the 3rd axis. Consequently this 'pollution' axis can be mapped in the region under study. The map shows (Fig.3) clearly evidence of a major contamination situation (the areas with positive values of this factorial index), which corresponds to the sectors where intensive agricultural activity occurs.

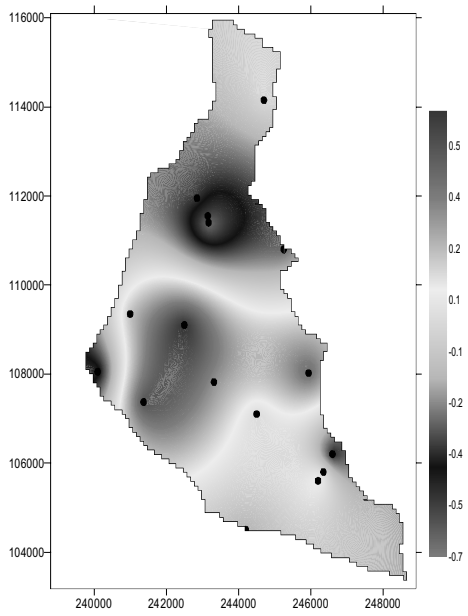

Figure 3. Spatial distribution of factorial index 3 in the area of the aquifer

RISK MAPS

Iso-probability map of nitrate exceeding 50 mg/L, was also calculated after a binary coding of nitrate concentration values (a value equal to 1 was assigned when concentrations exceeded 50 mg/L and a value equal to 0, otherwise). Maps were built in a GIS environment by using geostatistical interpolation method (Paralta and Ribeiro, 2001). The map (see Fig.4) shows highest probabilities located in the southwest and center areas, and also in the top east zone, coincident with dry cereal crops (compare with Fig.2).

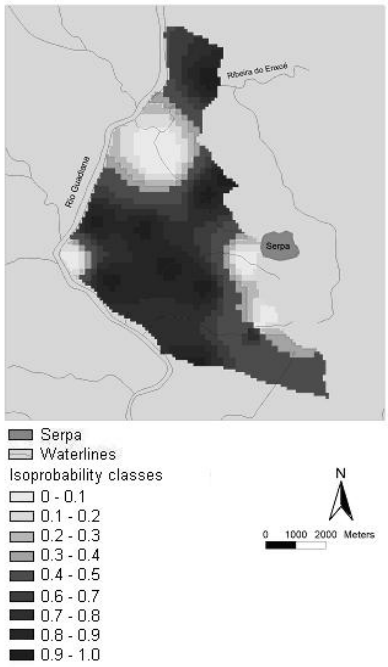

Figure 4. Nitrate isoprobability map (at high season)

APPLICATION OF THE SUSCEPTIBILITY INDEX

The vulnerability maps constitute a set of tools that were developed with the aim of preventing groundwater pollution. These maps define spatially the degree of protection of an aquifer to anthropic and natural pollution.

A Susceptibility Index (SI) was developed (Ribeiro, 2000) with the aim of evaluating the specific aquifer vulnerability to agricultural contamination on the basis of DRASTIC index (Aller *et al*. 1987) taking into account an additional parameter: the land use and all the impacts associated. SI is the weighted sum of five parameters (see eq. 1): Depth to the water table (D); annual recharge (R); aquifer lithology (A); topography (T) and land use type (LU). Weights were inferred on the basis of a Delphi panel of Portuguese specialists

$$SI_i = 0.186D_i + 0.212R_i + 0.259A_i + 0.121T_i + 0.222LU_i \quad (1)$$

for each cell i

SI map (Fig.5) shows a high frequency for the class {40-50}. Once more the most susceptible areas correspond to the agricultural land use, where the main production is the wheat. This evidence is also clear when we compare the risk and SI maps.

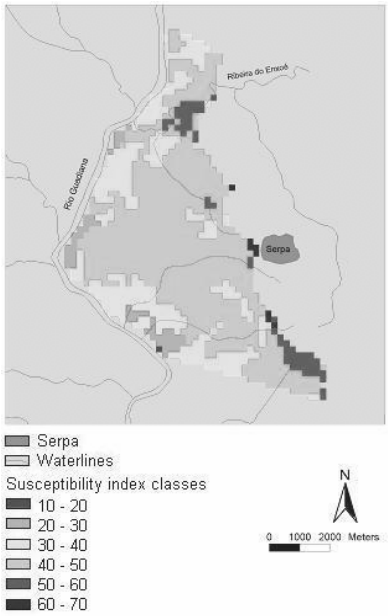

Figure 5. Susceptibility Index Map

CONCLUSIONS

Results show clearly that due to decades of excessive fertilization, diffuse agricultural pollution is fairly widespread in this sector of "Gabros de Beja" Aquifer System. In fact several images obtained by different geomathematical methods, PCA, geostatistics and vulnerability indexes proof that there is a correspondence between high susceptibility areas to areas where both agricultural activities exist and high nitrate concentrations are observed. This situation must be urgently changed, according to the EU Nitrate Framework Directive and EC Water Framework Directive.

REFERENCES

Aller L, Bennet J, Lehr R, Petty, Hackett (1987) DRASTIC: A Standardized System for Evaluating Groundwater Pollution Potential Using Hydrogeologic Settings. NWWA/EPA Series, US Environmental Protection Agency, Ada, Okla

Paralta E, Ribeiro L (2001). Stochastic Modelling and Probability Risk Maps of Nitrate Pollution in the Vicinities of Beja (Alentejo, South Portugal). In Ribeiro L (ed) Proc of 3rd International Conference on Future Groundwater Resources at Risk (FRG'01), pp 251-261, CVRM/IST, Lisbon, Portugal

Ribeiro L (2000) Development of a susceptibility index to be used in agricultural diffuse pollution", internal report, 9p, ERSHA/CVRM

An overview of the hydrogeology of the Precambrian basement in Quebec and related mining problems

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A b s t r a c t : Groundwaters in the Precambrian basement are not used in large quantities in Québec, even though the basement underlies more than 90% of Quebec's surface area. Nevertheless, mining and hydroelectric power generation provide valuable data and study sites on hydrogeological, geomechanical and geochemical processes, and their interactions, around underground excavations. A decrease in permeability with depth and the occurrence of brines with high chloride content are also frequently observed in this environment.

INTRODUCTION

The principal interaction between groundwater and human activities in various geological environments, including the Precambrian basement, varies from one region of the World to the other (Gustafson and Krásný 1994). Mine drainage represents a characteristic hydrogeological problem in the Canadian Shield, particularly in Quebec (Charron 1967; Brown 1970; Rouleau *et al.* 1999a&b). Radioactive waste disposal (Farvolden *et al.* 1988) and hydroelectric power generation have also motivated local hydrogeological studies and observations in the bedrock of this region.

This presentation is an overview of the hydrogeology of the Precambrian basement in Quebec, describing a number of hydro-mechanical and hydro-chemical phenomena affecting mine drainage.

GEOLOGY, HYDROLOGY AND CLIMATE

The Precambrian basement, which underlies more than 90% of Quebec (Fig.1), forms part of the Canadian Shield which is divided into geological provinces according to deformation style and age (Stockwell 1962).

Total annual precipitation ranges from about 1100 mm in the southern part of the Precambrian Shield to about 400 mm in the northern tip of Quebec (Lapointe 1977; Proulx *et al.* 1987). This decrease in precipitation, combined with the presence of more or less discontinuous permafrost over much of the area, results in considerably lower groundwater recharge at higher latitudes (Rouleau *et al.* 1999b).

GROUNDWATER WITHDRAWAL

Local hydrogeological data are essentially restricted to the most populated areas of the Precambrian Shield in Quebec, which are located in the Grenville Province (Rivers *et al.* 1989) and in the Abitibi Subprovince of the Superior Province (Hock 1994). However, even in these areas groundwater is not used in large quantities because of the wide availability of surface water (i.e. lakes and streams). The groundwater is essentially drawn from permeable glacial and pro-glacial deposits, and is used by municipalities and industries. Mine drainage constitutes the main groundwater withdrawal and is responsible for the characteristic hydrogeological problem in the crystalline basement formations in Quebec (Rouleau *et al.* 1999b). In the Abitibi geological Subprovince as an example, which covers about 90,000 km^2 of the Precambrian Shield, the total groundwater withdrawn from the 35 mines (in 1993) of that region amounts to about 57,000 m^3/day (MEFQ 1993). This is roughly equivalent to the groundwater withdrawn by the 150,000 inhabitants of this mining region for all other usages, including drinking water, pisciculture and other industries.

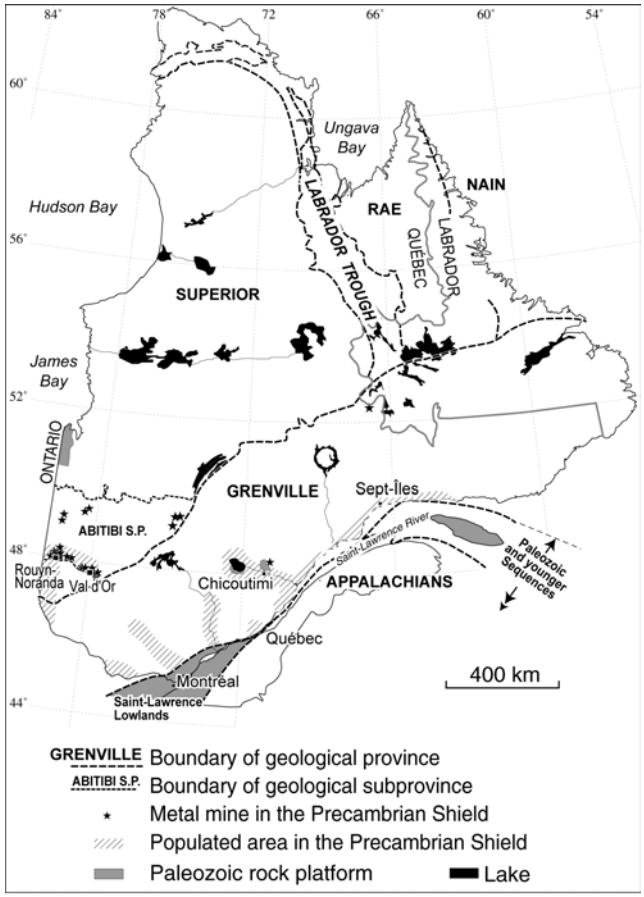

Fig.1 Map of the geological provinces in the Precambrian Shield in Quebec and Labrador, showing the location of mines

HYDRO-MECHANICAL AND HYDRO-GEOCHEMICAL PHENOMENA

Minor fractures and major structural discontinuities, such as faults and shear zones, clearly control groundwater inflow to a depth of about 300 m in the mines (Raven and Gale 1986). At greater depth, major structures alone generally constitute the groundwater conduits.

Excavation in a rock mass disturbs the geomechanical stress field, which in turn presumably affects the hydrogeological properties of the rock mass. However, field data on rock permeability around excavations suggest that other processes may also affect the hydrogeological properties of a rock mass around drained excavations, such as groundwater degassing and dissolution-precipitation along fracture planes (Rouleau *et al.* 1999a).

Many occurrences of brines and gases have been reported in the Canadian Shield (Fritz and Frape 1982; Guha and Kanwar 1987; Sherwood *et al.* 1988), including in the mines in Quebec. These brines are mostly encountered at a depth of 1000 m or more, and typically have high chloride content.

Groundwater drainage in mines often produces an important drawdown cone. The presence of air in this enlarged unsaturated volume of rock increases geochemical reactions affecting groundwater (Rouleau *et al.* 1999a).

CONCLUSION

Mine drainage constitutes the main groundwater withdrawal and presents a characteristic hydrogeological problem in the Precambrian basement in Quebec. Mining and other underground excavations often have significant effect on the hydrogeological properties of a rock mass as well as on the groundwater quality and flow regime.

REFERENCES

Brown IC (1970) Groundwater Geology. In: Douglas RJW (ed) Geology and Economic Minerals of Canada. Geol Survey of Canada, Econ Geol Rep 1:766-791

Charron JE (1967) Canadian Shield hydrogeological region. In: Brown IC (ed) Groundwater in Canada. Geol Survey of Canada, Econ Geol Rep 24:120-130

Farvolden RN, Pfannkuch O, Pearson R, Fritz P (1988) Region 12: Precambrian Shield. In: Back W, Rosenshein JS, Seaber PR (eds) Hydrogeology. The Geology of North America, v.O-2:101-114

Fritz P, Frape SK (1982) Saline groundwaters in the Canadian Shield – A first overview. Chemical Geology 36:179-190

Guha J, Kanwar R (1987) Vug brines – fluid inclusions: A key to the understanding of secondary gold enrichment processes and the evolution of deep brines in the Canadian Shield. In: Fritz P, Frape SK (eds) Salines Water and Gases in Crystalline Rocks - Geol Assoc of Canada, Spec Paper 33:99-101

Gustafson G. and Krásný J. (1994): Crystalline rock aquifers: their occurrence, use and importance. Applied Hydrogeology 2, 2:64-75.

Hocq M (1994) La Province du Supérieur. In: Géologie du Québec. Ministère des ressources naturelles du Québec, MM94-01:7-20

Lapointe D (1977) Les régimes hydrologiques du Québec septentrional. Service de l'hydrométrie, Ministère des richesses naturelles du Québec, HP 41, 203 pp

MEFQ (1995) Bilan annuel de conformité environnemental – Secteur minier – 1993. Ministère de l'Environnement et de la Faune du Québec, 149 pp

Proulx H, Jacques G, Lamothe A-M, Litynski J (1987) Climatologie du Québec méridional. Direction de la météorologie, Ministère de l'Environnement du Québec, MP 65, 198 pp

Raven KG, Gale JE (1986) A Study of the Surface and Subsurface Structural and Groundwater Conditions at Selected Underground Mines and Excavations. Atomic Energy of Canada Ltd, Pinawa, TR-177, 81pp

Rivers T, Martignole J, Gower CF, Davidson T (1989) New tectonic divisions for the Grenville province, southeast Canadian Shield. Tectonics 8:63-84

Rouleau A, Archambault G, Carignan J, Benlahcen A (1999a) Examples of hydrogeological, geomechanical and geochemical factors affecting underground mine dewatering. In: Hydrogeology and Land Use Management - Proc XXIX Congress Int Assoc of Hydrogeologists, Bratislava, Slovakia, 809-814

Rouleau A, Guha J, Archambault G, Benlahcen A (1999b) Aperçu de l'hydrogéologie en socle précambrien au Québec et des problématiques minières. Hydrogéologie 1999 4:23-31

Sherwood B, Fritz P, Frape SK, Macko SA, Weise SM, Welhan JA (1988) Methane occurrences in the Canadian Shield. Chemical Geology 71:223-236

Stockwell CH (1962) A tectonic map of the Canadian Shield. In: Tectonics of the Canadian Shield - The Royal Society of Canada, Spec Publication 4:6-15

Active groundwater monitoring and remediation during tunnelling through fractured bedrock under urban areas

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A b s t r a c t : Real time monitoring is being used to control inflow and pregrouting for a new tunnel in the Oslo area. Detailed site investigations and vulnerability studies were used to define accept criteria. Further hydrogeological mapping and modelling were used to form a strategy to minimize the need for remediating disturbances and damages due to an unwanted reduction of the groundwater level. During construction, the control of inflow and thus control of the groundwater balance is performed by use of instrumentation and automatic performance monitoring. The continuous updating of the groundwater levels and soil pore water pressures above the tunnels has enabled the contractor to respond quickly by changing the pre-grouting procedure due to any recorded change in groundwater level above the tunnel. The leakage inflow in the tunnel is below the allowable rates for the different classified areas.

INTRODUCTION

During recent years, tunnelling under urban areas in Norway has focused on groundwater control and pre-grouting strategy in order to reduce negative environmental effects. In 1999, there were particular challenges with the excavation of a 13.8 km long high-speed railway tunnel in gneissic bedrocks between the capital and its new international airport 40 km to the north. Large unexpected leakages of water occurred in the tunnel at several areas with extremely fractured bedrock. This led to significant decreases of soil pore pressures and groundwater levels above the tunnel. As a result there were large settlements and damages to buildings and forest areas situated on the natural soil deposits above the tunnel. A permanent water injection system had to be established to raise the groundwater level and pore water pressures to original conditions in order to prevent further settlements.

The experiences made in the design and construction of the above tunnel led to new research and an improved precautionary approach in the planning of groundwater balance control and pre-grouting strategy for construction of the new railway tunnels. This new approach was fully implemented during the construction of a new 7.3 km long tunnel for double-track high-speed railway currently being constructed between Jong and Asker, south of Oslo.

SITE INVESTIGATION

A comprehensive site investigation program was carried out incorporating previously recorded data from other nearby tunnel works and detailed topographical mapping. The program revealed that the geology of the area is quite complex with volcanic rocks from the Permian age overlaying sedimentary rocks (shales, phyllite and calcarerous shales). The area has intrusions of near vertical dykes (dolerite). The bedrock cover above the tunnel is mainly between 50-80 m, but sometimes as low as 2 m. The tunnel is between 20 m and 100 m above sea level.

The soil investigations have shown that there are soft marine clay and silt deposits above bedrock. There are also some glacio-fluvial sands and gravels in the interface zones at bedrock surface, which are typical for the Oslo region. The thickness of the soil deposits is mainly between 0 m and 28 m along the tunnel. It is well known that the soft clays are sensitive to decrease in natural groundwater levels from water leakage into rock tunnels, which has earlier resulted in severe settlements.

VULNERABILITY STUDY AND ACCEPTANCE CRITERIA

The area nearby the tunnel is densely populated, also encountering grounds with valuable recreational purposes and special sensitive biotopes. Vulnerability and sensitivity of buildings, infrastructures, lakes, bogs, swamps, streams and springs is dependant on changes in groundwater levels and surface water storage in the soil deposits and bedrocks. Such changes in groundwater conditions in the catchment area reflect the ”water balance”, that is the difference between the precipitation and the combined natural run off from the area, evapotranspiration from surface and leakage into the tunnel. The vulnerability study is used to determine an acceptance criterion for leakage volume into the tunnel to reduce negative effects on the environment.

The tunnel was first sectioned and classified according to anticipated problems with respect to vulnerability and sensitivity of the surrounding environment. Secondly, more than 100 households currently using groundwater from local wells as their primary or secondary source of fresh water supply were classified. And lastly, the vegetation, recreational areas and special biotopes along the railway tunnel were classified based on their sensitivity for potential lowering of groundwater level and on their utilization. By combining the sensitivity for potential damages to the environment with damages due to settlements, three classes of allowable leakage rates were established: (class 1) moderate tunnel leakage 8-16 L/min/100 m, (class 2) low leakage rate 4-8 L/min/100 m and (class 3) extremely low leakage rate less than 4 L/min/100 m.

HYDROGEOLOGICAL MAPPING AND MODELLING

The water conditions in the area were mapped over a period of several years ahead of the tunnel construction works in order to assess the natural seasonal and annual variations in groundwater levels. The monitoring comprised recordings of water level fluctuations in lakes and groundwater aquifers, pore water pressures in the soil sediments, and flow in rivers and streams.

The effect from precipitation and evapotranspiration on groundwater conditions was well known from daily recorded climate data at several meteorological stations in the area. Studies were made to estimate the actual size of the catchment and influence areas of the tunnel, taking into consideration the bedrock geology. Recorded data on seasonal and annual

variations in run-off of water in the area were obtained from Norwegian Water Resource and Energy Administration.

The permeabilities of the marine clays above bedrock and of the coarser sediments in the transition zone were investigated.

The permeability of the bedrocks was established by Lugeon testing (water leakage-pressure testing) in the core drilled holes which are subsequently used for the groundwater monitoring. The areas with intrusions of near vertical dykes (dolerite) may in some cases act as barriers for groundwater flow and in other cases act as water bearing structures with higher permeability than that of the surrounding rocks.

Using the results of the comprehensive ground investigations and the mapping of groundwater conditions, the amount of acceptable leakage inflow into the tunnel was determined using numerical hydrogeological modelling.

CONSTRUCION AND GROUTING STRATEGY

The tunnel cross section is 104 m^2 and is being excavated by drilling and blasting techniques, supported mainly by bolts and shotcrete. Water control is achieved by the use of probe-drilling ahead of the tunnel face followed by pre-grouting of the rock mass. The grouting program includes use of very fine micro-cements, cement additives and modern equipment using high grouting pressures. The pre-grouting is being carried out in sequences of 3 or 4 blasting rounds depending on the classification. The length of each grouting sequence is 21-27 m and supplementary holes are being drilled depending on inflow leakage of water. The primary parameter for changing the grouting effort is the response of the groundwater level. The strategy also includes measures for temporary water recharge or injection in boreholes to achieve water balance during grouting.

MEASUREMENT RESULTS

The instrumentation system for automatic performance monitoring on the Jong-Asker tunnel project has so far during the first year of excavating proven to be very useful for the contractor and the owner at site. A continuously updating of the groundwater levels and soil pore water pressures above the tunnels enable the contractor to respond quickly by changing the pre-grouting procedure due to any recorded change in groundwater level above the tunnel.

A typical example of results of measurement is shown in Fig.1 for well station K6 adjacent to the Skaugum area. The water level in this well decreased significantly 3.5 m on December 18, 2002 during drilling of holes for pre-grouting. The level increased 2.0 m during subsequent cement grouting, however not to the original level. Therefore, additional pre-grouting holes were drilled January 7, 2003 and subsequent temporary water injection and final cement pre-grouting resulted in a permanent increase to the original water level.

By following the planned grouting strategy to achieve water balance, verified by the automatic performance monitoring system, the leakage inflow in the tunnel has up to now been kept below the allowable rates for the different classified areas. The leakage measured for the whole length of the excavated tunnel so far, is equal to 5 L/min/100 m. No settlements have so far been measured on the 600 buildings and the recreational areas subject to monitoring.

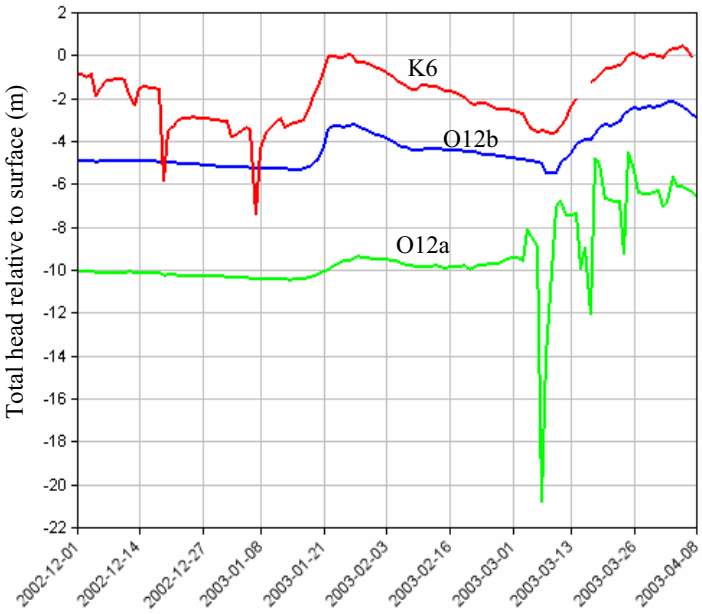

Figure 1. Continuous record of groundwater levels

Different hydraulic properties of single fractures in argillaceous medium: the case of the IRSN Tournemire site (France)

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A b s t r a c t : Different studies carried out on the argillaceous IRSN Tournemire site showed the occurrence of several types of discontinuities (fault and fracture) at different scales. The hydraulic properties of these structures are investigated by conducting *in situ* hydraulic tests. In a first step, we focused on both single isolated fractures, mainly filled by calcite and water-producing fractures with geodic cavities. Transmissivities determined by pulse test on sealed fractures range from $1.2.10^{-13}$ m^2/s to 2.10^{-14} m^2/s. The values are of the same order than that measured on an unfractured zone (matrix). The slug and pulse tests on the fractures with geodic cavities give a range of transmissivities from 1.10^{-10} m^2/s to 4.10^{-10} m^2/s. These results suggest that these discontinuities might correspond to a possible preferential pathway for fluid migration.

INTRODUCTION

Deep indurated argillaceous formations have intermediate properties between plastic clay (transport processes dominated by matrix diffusion) and hard rocks like granite (preferential advection through water-conducting fractures).

The Tournemire claystone (Aveyron, France) belongs to these formations where several types of discontinuities at different scales occur (Cabrera *et al.* 2001). One part of the project aims at evaluating the possibilities and processes of fluid migrations through the argillaceous formation, particularly through these discontinuities.

This study is focused on the hydraulic properties of single sealed fracture zone and water-producing fractures with geodic cavities.

Table 1. Characteristics of hydraulic tests

	Borehole	Used Fluid	Test type	Duration of test
Matrix	PH1 1.1 m long	Synthetic water close to matrix water	Pulse with compressibility measurement	1 year
Sealed fractures	ID-180 Three chambers (1.5 m long)	Ca-HCO_3 Water from upper aquifer	Pulse without compressibility measurement	3d
Fractures with geodic cavities	M2 0.5 m long	In situ water	Pulse with compressibility measurement	30 d
	TN2 0.5 m long	In situ water	Slug	1 year

GEOLOGICAL SETTING

The Tournemire site is located in sedimentary jurassic formations on the Southern border of the French Central massif. The argillaceous formations, 250 m thick, are located between two limestone and dolomite layers (300-500m thick).

The argillaceous medium corresponds to well-compacted argilites and marls with a predominant clay fraction (40-50 %). The matrix shows a very low water content (1 to 5 % wt), with poral space around 2.5 nm. (Dewindt *et al.* 1998).

The Tournemire site is a sub-horizontal monoclinal structure affected by regional E-W striking major Cernon fault (80 km lenght) in the northern part. The massif is also affected by some secondary faults of hectometric scale, which are associated with fractured zones (Fig.1). Lastly, fissures of metric to decametric scale were observed.

The paleo-stress analyses indicate that most of this fracturation is related to the compressional N-S to NW-SE trending Pyrenean tectonics (40-50 Ma ago) (Constantin *et al.* 2002). All these fractures are generally filled with calcite with occurrence of cubic pyrite. However, this compressional phase created some apertures, with geodic cavities, mainly located in the relay zones. Discharges of water occur in these geodic systems (Cabrera *et al.* 2001).

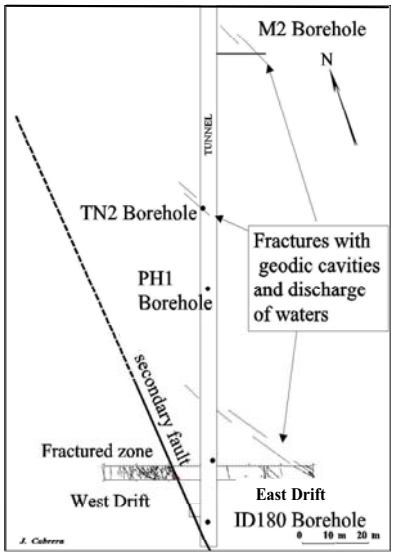

Figure 1. Structural sketch of Tournemire site with the location of the boreholes

METHODS

Several hydraulic-conductivity test campaigns (Slug and Pulse tests) were performed to characterize the properties of matrix, sealed fractures and fractures with geodic cavities. Long-term hydraulic monitoring was conducted on the PH1 borehole to determine the properties of the matrix (Bertrand *et al.* 2002). Three short duration tests (< 3d) were realized at different levels in the ID 180 borehole in chambers crossed-cut zones with single sealed fractures (Boisson *et al.* 2001). Pulse and slug tests were carried out on M2 and TN2 boreholes to study the hydraulic behaviour of the fractures with geodic cavities (Fig.1). Tab.1 summarizes the three configurations.

RESULTS

All the tests were interpreted or re-interpreted by means of the log-log analysis of the slug/pulse test data using constant rate type curves with zero well-bore storage (Peres *et al.* 1989, Chakrabarty and Enachescu 1997). This technique is illustrated in the Fig.2.

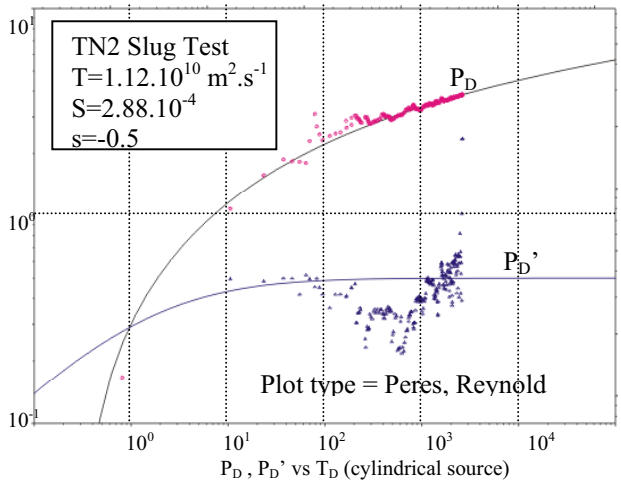

Figure 2. Interpretation of slug test on TN2 borehole

Tab.2 presents all the results obtained by using the deconvolution analysis and shows very large differences in transmissivity and storativity. As the compressibility (C) was not measured in the case of the tests on the sealed fractures, we used estimates (C of water and C of system with hydralic packers), which lead to some inaccuracy. Most of these tests, conducted on the sealed fracture, gives results in the same order of magnitude of that conducted on the matrix. One exception is the K5 test that gives four orders of magnitude higher transmissivity. Indeed, this borehole was drilled with water, excluding any possibility to observe water production. This test is thus assumed to integrate water production and indicates that the fracture was not completely sealed.

Type	Borehole	C 10^{-10} Pa^{-1}	T 10^{-14} $m^2.s^{-1}$	S 10^{-6}	b µm
Sealed fracture	ID180	10 *	4.2	12	20
	K3	5 *	2	6	5
	ID180	10 *	12	3.6	5
	K4	5 *	8.3	2.6	4
	ID180	10 *	5200	0.8	1.2
	K5	5 *	2600	0.4	0.5
Matrix	PH1	30	1.85	1.2	
Fractures with	TN2	Slug	11000	290	72
Geodic cavities	M2	1000	41000	50	200

Table 2. Results of hydraulic test interpretation. C is compressibility of the isolated section, * not measured C. b fracture thickness derived from Wang *et al.* (1977)

Other tests of the ID-180 borehole (K3 and K4) show hydraulic characteristics close to that determined on the matrix and therefore indicate the very good sealing of the fractures.

The tests carried out on fractures with geodic cavities give the highest transmissivities. The values obtained on these tests are of the same order of magnitude, although assumed to make part of two distinct fracture systems.

DISCUSSION

The large transmissivity values obtained on producing fractures suggest the existence of circulations in the site. This result is consistent with the presence of active radiocarbon in waters, which indicates a recent circulation and the renewal of waters in the argillaceous formation (Beaucaire *et al.* in prep.).

According to Cabrera *et al.* (2001), the geodic cavities are linked to relay zones between simple fractures (Fig.3). This study showed that these cavities might act as a possible preferential pathway to circulation.

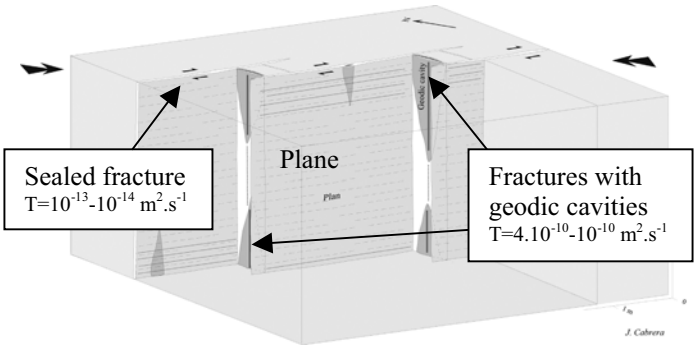

Figure 3. Summarize of results in a schematic diagram of the structure with geodic cavities

On the contrary, the sealed fractures that can be located very near to the cavities, even in the same system (Fig.3.), have hydraulic properties close to that of matrix, which demonstrates the great hydraulic heterogeneity of these discontinuities at a very small scale.

The forthcoming studies will focus on the spatial extent of these structures and on their degrees of connectivity by means of interference tests and artificial tracer tests coupled with structural and geophysical investigations and geochemical analyses of water inflows (origin, age).

REFERENCES

Beaucaire C, Savoye S, Michelot JL, Cabrera J (2003) Groundwater characterisation and modelling of water-rock equilibria in the Tournemire argillaceous formations (Aveyron, France) in prep to Applied Geochemistry

Bertrand L, Laviguerie R, Cabrera J, Matray JM, Savoye S (2002) Instrument for measuring pore pressure and permeability in low permeability rock. In: Intern. Meeting Clay in natural and engineered barriers for radioactive waste confinement Reims, France

Boisson JY, Bertrand L, Heitz JF, Moreau-Le Golvan Y (2001) In situ and laboratory investigations of fluid through an argillaceous formation at different scales of space and time, Tournemire tunnel, southern France. Hydrogeol J 9:108-123

Cabrera J., Beaucaire C., Bruno G., De Windt L., Genty A., Ramanbasoa N., Rejeb A. Savoye S. et Volant P. (2001) Le projet Tournemire comme support de l'expertise sur le stockage profond en milieu argileux : synthèse des programmes de recherche. Rapport IRSN/SERGD 01-19

Chakrabarty C, Enachescu C (1997) Using the deconvolution approach for slug test analysis: Theory and application. Ground Water 35(5):797-806

Constantin J, Vergély P, Cabrera J (2002) Tectonique et fracturation associé dans les bassin des Causses (Aveyron, France): le cas du secteur de Tournemire. Bull Soc géol Fr 173(3):229-443

Dewindt L, Cabrera J, Boisson JY (1999) Hydrochemistry of an indurated argillaceous formation (Tournmire site, France) In: Ah=rehart and Hulston (eds) Water rock Intercations, Taupo (NZ) 145-148

Peres AMM, Onur M, Reynolds A (1989) A new analysis procedure for determining aquifer properties from slug test data. Water Ressour Res 25(7):1591-1602

Savoye S, Beaucaire C, Matray JM (2002) Caractérisation Hydraulique Des Fractures Simples Avec Arrivées d'eau à Tournemire: Description et Premier Bilan de L'instrumentation en Forage. Rapport IRSN/SERGD 02-38

Wang J, Tsang CF, Narisimhan TN, Witherspoon PA (1977) Transient flow in tight fractures. In: Proc 1st Int Well Testing Symp, Lawrence Berkeley Laboratory, USA 103-113

Development of technology of groundwater pollution assessment and environmental research in the Karabash Region

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A b s t r a c t : The results are presented of researches and modeling of distribution of ecologically dangerous elements in the geological environment of the Karabash area (Southern Ural). The model was constructed on the basis of the geological data about fractured rocks and of tectonic faults location. On this basis sites are allocated for the control of underground waters pollution with geophysical methods.

The research was focused on the Karabash town area (Southern Urals) (fig.1), which, as it is well known, is one of the areas on the planet most intensively polluted by heavy metals as a result of a hundred years history of excavation and processing of complex ores. At present, within the town, local areas are found, the soil of which contain mercury in concentrations 700 times exceeding MPC.

Main sources of the environment pollution and specifically contamination of waters used for water supply in the Karabash city are:

- atmospheric discharges of the Karabash copper-smelting plant – toxic elements driven to the air settle out as far from the plant as in the radius of 10 km:
- infiltration of precipitation and seasonal surface waters through slime storages and settling basins;
- self-outflow and filtration of mining waters with high concentrations of heavy metal ions, the latter supplied by natural leaching of polymetallic ore when left intact.

Heavy metals such as As, Pb, Fe, Cu, Hg and others finally reach the surface of city water supplies (the Serebry lake, Bol'shoy Kialim river water storage, and the Argazinskoe reservoir, which is also a water resource for the city of Chelyabinsk). Surface and mining waters easily permeate into fracturing (faults) zones with high coefficient of filtration. After reaching some depth they contaminate underground waters that used to be a source for centralized population water supply. Waters containing heavy metals discharge onto the land's surface along fault zones (it occurs at the hypsometrical level under 300 m above see level) and contaminate surface waters.

Ours operations include the solution of the following problems:

1. Collection of data for the region and creation of a cartographic data base on GIS-technology characterizing the geological, tectonic, hydrogeological peculiar features, and the character of pollution of the geological medium.
2. The development of a device allowing, by the neutron method, to carry out an operative control of the content of heavy metals in the surface and subterranean waters in the real time regime.
3. To conduct geological-geophysical research with the purpose of finding the major structural-tectonic dislocations and the potential channels of distribution of ecologically dangerous substances in the geological medium.
4. Construction of a model of filtration and distribution of polluting substances by underground waters taking into account the tectonic structure and relief of the Karabash town area.

Prominence was given the research of the relation between velocity and amount of dangerous elements transferred with underground water and the jointing of the upper part of the rock massif. The plan of work was the following. First rock jointing was studied with geological and geophysical methods, then soils and water were sampled on the profiles from the pollution source to Argazinskoe water storage basin. In Fig.2 the scheme of field work in the bash area is given.

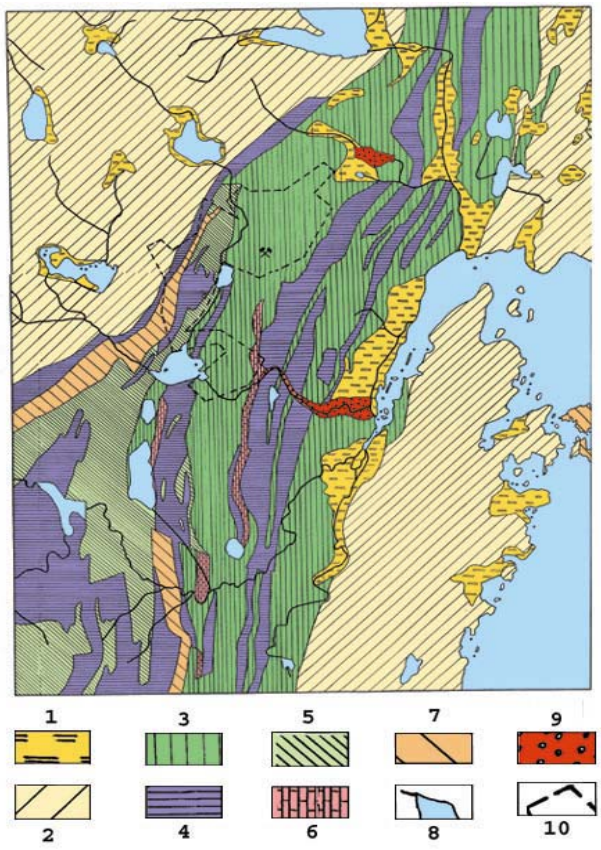

Figure 1. Hydrogeological map of Karabash region
1 - Water-bearing complex of the Quaternary alluvial sediments; 2 - Water-bearing complex of the Sysert-Ilmenogorskiy in the southeast and Ufaleiskiy in the northwest anticlinoria fractured zones composed of Precambrian metamorphic rocks; 3 - Water-bearing complex of the fractured zones of the Karabash synclinorium volcanic sedimentary rocks; 4 - Water-bearing complex of the fractured zones of intrusive ultrabasic rocks and serpentinites; 5 - Water-bearing complex of the fractured zones of intrusive basic and medium rocks; 6 - Water-bearing complex of the fractured zones of carbonaceous rocks ; 7 - Water-bearing complex of the fractured zones of granitoid rocks ; 8 - Lakes and rivers ; 9 - Areas of basins technogenic pollution with mine drains and tailings ; 10- Contour of the residential and industrial building of Karabash city

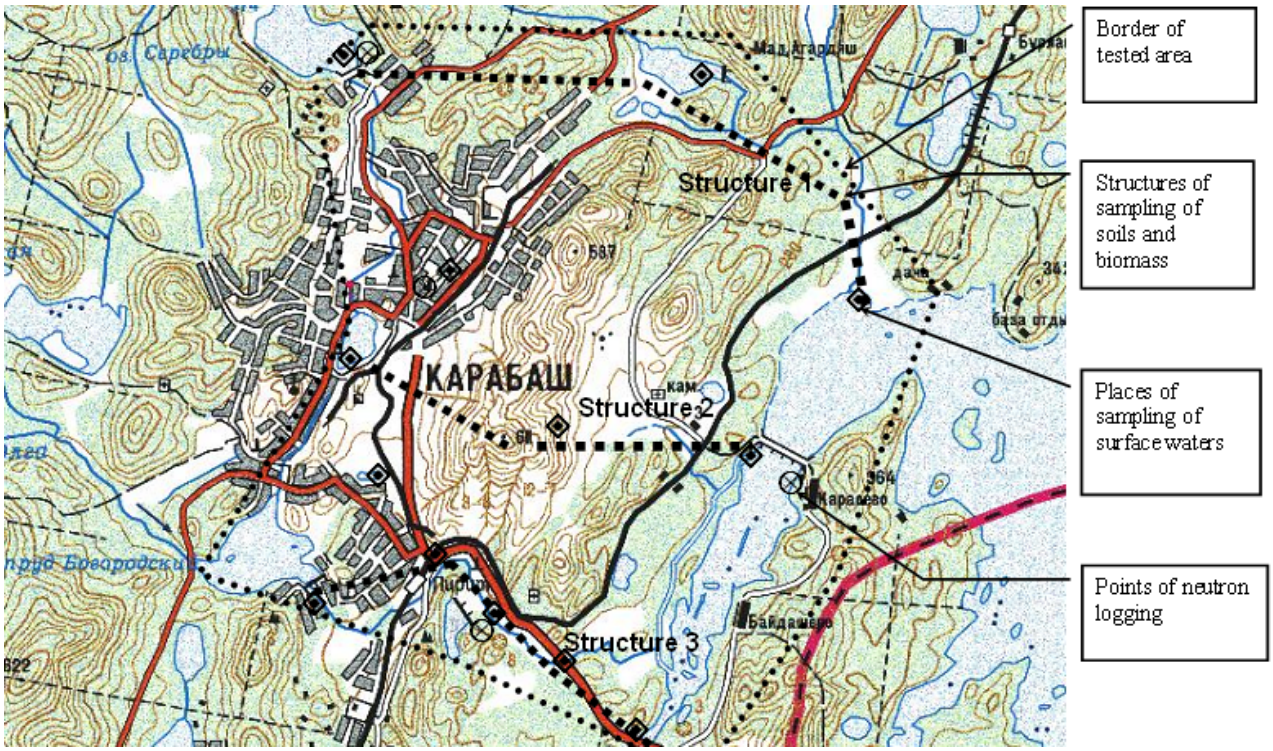

Figure 2. The scheme of field work and sampling

Sampling profiles oriented in the direction of maximum variation (maximum gradient) of environmental pollution mostly in the eastern direction and go out of the zone of the influence of the city enterprises. On the profiles, rock jointing was measured and soils, biomass and surface water were sampled for laboratory analysis. On the profiles, points were specified where heavy metals content would be promptly determined with the use of neutron method in the field.

The results of research were reported in (Report 2002). The constructed model of major pollutants spread with surface and underground water as well as field observations data showed that in the central area the transfer goes from north to south parallel to the major zones of jointing up to the Sak-Elga River.

In this case, fault zones extending from north to south play an important role as well as sections of technogenic disturbances of the geological environment in the areas of abandoned deposits at a depth of 500 m. Them the direction turns to westward and the major part of pollutants is transferred with surface water. Greatest pollution is noted in the upper part of the Sak-Elga river valley.

REFERENCES

Report on the project INCO-Copernicus "Toxic Pollution Detection in Ground Water from Real Time Early Warning to Overall Assessment". (Contract ICA2-CT2001-0016). 2002

The impact of industrial effluents on water quality in a geologically contrasting terrain, Andhra Pradesh, India

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The Patancheru and Bolaram IDAs ($78^0$08'-$78^0$23' east longitude and $17^0$30'-$17^0$40' north latitude) of Medak dist. are located at a distance of about 35 km north-west from Hyderabad, A.P. There are a number of industries engaged in the manufacture/production/processing of pharmaceuticals, paints and pigments, metal treatment and steel rolling, cotton and synthetic yarn and engineering goods operative since 1977, that use various inorganic and organic chemicals as raw material. Apart from discharge of effluents into the streams, the semi-solidus wastes are burnt in open grounds. The Pamula vagu, Pedda vagu and Nakka vagu while carrying the effluents act as a diffuse source all along their course

The Patancheru and Bolaram industrial areas are underlain by contrasting geological formations. The Patancheru and adjoining areas are covered with Nakka vagu alluvium of Recent origin. The Bolaram industrial areas are covered with granite rocks of Archaean gneiss complex. Nakka vagu and its tributaries- Pamula vagu and Pedda vagu that originate in the northeastern and southeastern parts of the area drain the study area (Fig.1). In general, the drainage of the granite terrain is sub-parallel to dendritic. The alluvium all along Nakka vagu is composed of sediments ranging from clay to gravel. Two facies of deposition are observable: (a) the near surface comprises of silt and clay and (b) the deeper consists of sand and gravel (fine).

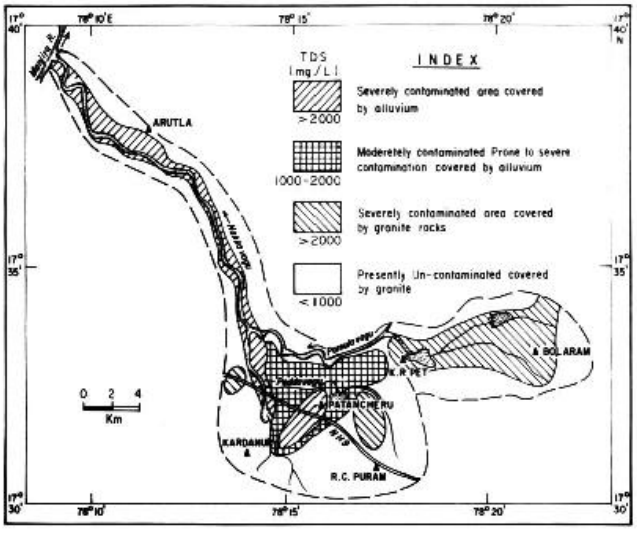

Figure 1. Map showing different stages of contamination

Red loamy soils of few centimeters thickness cover the granite terrain. The area underlain by granite has a variable thickness of weathered zone ranging from 10 to 20 meters that is followed by fractured and massive rock. The hydrological details from wells inventoried are given Tab.1. The transmissivity of the granite aquifer varies from 30 m^2/day to 160 m^2/day. A higher transmissivity (such as 430 m^2/day) in the granite aquifer is attributed to highly fractured zones. In the alluvial aquifer the transmissivity varies from 750 m^2/day to 1315 m^2/day. Though the aquifers of granite possess high transmissivity, the storage coefficient is less (x 10^{-4} to 10^{-5}). The alluvial aquifer has a high transmissivity and also high groundwater potential (storage coefficient about 10^{-2}).

Table 1. Hydrological details of abstraction structures

A. Depth particulars of wells

Dug wells		*Bore wells*		*Filter point wells*	
Total depth	No. of wells	Total depth	No. of wells	Total depth	No. of wells
<10 m	20	<30 m	10		
					> 50
10 -15m	40	30 -50 m	50	8 -13 m	m
>15 m	5	>50	20		
B. Water table					
1.0 - 12.0 m		3.0 - 25.0 m		4.0 - 8.0 m	
C. Yield of wells					
5.0-200 m3/d		110 –300 lpm		75 -180 lpm	
		dd 5-15 m		dd 1-3m	

None of the water sources (groundwater and surface) are found fit for drinking purposes as per Indian Standards Institute (1983) norms. Based on total dissolved solids Davies and Dewiest (1966) have proposed a three fold classification of groundwater for (a) domestic (< 500 mg/L), (b) irrigation (500 to 1000 mg/L) and (c) industry (>1000 mg/L). According to this classification only one sample falls under category (a), 10 samples under category (b) and 26 samples under category (c). Calcium and magnesium along with sulfates, chlorides and bicarbonates makes the water hard. The total hardness (TH) as $CaCO_3^-$ ranges between 240 and 2315 mg/L. It is inferred from the data that only 2 samples in dug wells and 3 samples in bore wells (about 14%) have the TH content below 300 mg/L, and the remaining samples exceed the limit and are the causative factors for encrustation on water supply systems. A high positive correlation between total hardness and Ca^{++}, Mg^{++}, Cl^- and SO_4^{--}, indicates that the hardness in groundwater is because of these constituents. Out of the 36-groundwater samples, about a quarter show high corrosivity ratio exceeding more than 1 indicating their intensive corrosive nature. The groundwater in the region is significantly dominated by the alkaline earths (Ca^{++} and Mg^{++}) over the alkalies (Na^+ and K^+). Interestingly, the strong acids (SO_4^{--} and Cl^-) exceed the weak acids (represented by HCO_3^-). Strong acids dominate about 75% of the samples, and only 25% consist of weak acids. The groundwater has secondary salinity indicated by non-carbonate hardness. In majority of the wells (66 %) the Schoeller index values indicate a base exchange reaction and the remaining 34 % samples show a negative value, which are due to cation-anion exchange. The values of the Schoeller index in 66% of samples are positive and alkaline earths have higher concentrations than bicarbonate, indicating exchange of sodium ions for alkaline earths and the water as base-exchange hardened water. About 19% of the samples are tending towards hardened water and the remaining 15% are base exchange softened water. About 75%of the wells are highly contaminated and are unsuitable for regular crops and perhaps may be used for salt resistant crops.

The effluent disposal on land causes metal corrosion, leaching and ultimately irregular adsorption on the soil particles leading to persistent environmental problems. Back (1966) introduced the concept of chemical facies as a means of

delineating the chemical character of groundwater. Though such progressive changes are not discernable due to multi-point sources of pollution, broadly they are classified as Sodium-chloride (43%), Sodium-bicarbonate (21%), Calcium-chloride (13%), Calcium-bicarbonate (7%), Magnesium-chloride (12%) and Magnesium-bicarbonate (4%) types.

The quality of the groundwater in the area has deteriorated significantly, indicated by the high concentration of Na^+, Ca^{++}, Cl^- and HCO_3^- ions, both in dug wells and bore wells, located in the vicinity of the effluent disposable sites. Since these wells are intersected by fractures/ joints (secondary porosity), the contaminated water percolates into the ground water system in due course of time and because of higher hydraulic conductivity is rapidly transported to other areas through advection related processes. Temporal variations in the quality of surface water and shallow aquifer are due to dilution by seasonal rainfall events. However, in contrast to shallow aquifer, the deeper aquifer is progressively deteriorating which would cause irreparable damage to the groundwater system.

The leachate formed due to precipitation reaches the shallow water table. As the pollutants diffuse into the pore spaces of the rock the 'dilution' will increase but the 'dispersion' will be greater. The total dissolved solids (TDS) concentration of treated effluents from the treatment plants is in the range of 4000 to 6,000 mg/L. The quality of groundwater in the region has been affected negatively due to the discharge of waste effluents on open lands, and into ponds, tanks and streams. The high values of electrical conductivity (EC), and concentrations of Na^+, Ca^{++}, Cl^-, and HCO_3^- indicate the impact of industrial effluents. Under natural conditions there should not be any anomalous ionic concentrations in groundwater and systematic changes in quality are expected in the groundwater flow path. Elevated ionic concentrations in the water can only be explained as due to contamination and mixing of foreign waters with natural groundwater. An area of about 2000 hectares in 22 villages situated mostly along the stream courses is affected due to which the farm yields are reduced significantly. Extensive evidence indicates that improper disposal of effluents has caused wide spread contamination.

The present studies made it possible to demarcate areas of contaminated groundwater and those prone to contamination in the near future (Fig.1). The area all along Nakka vagu upto a lateral extent of 500 - 600 m on the eastern part has deteriorated. The groundwater in and around Patancheru (upto a depth of 30m) has become hazardous.

REFERENCES

Back W (1966) Hydro chemical facies and groundwater flow patterns in northern part of Atlantic Coastal Plain. US Geol Surv Prof Paper, 498-A

ISI 1983 Indian Standards Specifications for drinking water, Indian Standard Institution, IS: 10500

Ryzner JW (1944) A new index for determining amount of calcium carbonate scale formed by water. Jour AWWA 30(4): 472 pp

Scholler H (1959) Arid zone hydrology. Recent developments UNESCO, 54-83

Hydrogeological monitoring during construction and operation of underground LPG storage facilities in mined caverns

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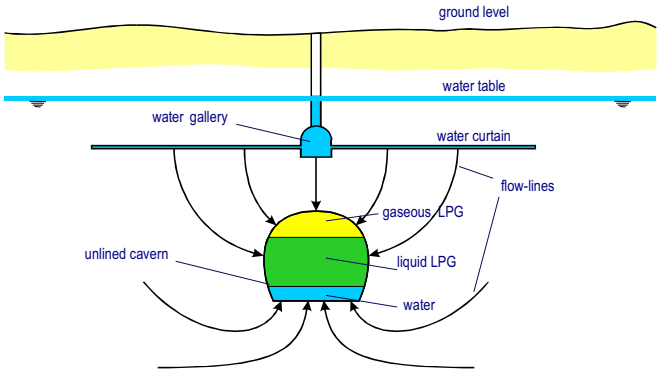
Abstract: The gas-tightness concept for underground LPG storage in unlined mined caverns is based on the hydrodynamic containment principle. To check the flow gradients for compliance with this rule, the cavern operating parameters, the pore pressure distribution in the cavern surrounding and the local hydrogeological environment are to be thoroughly monitored during cavern operation. Feedback from long-term data arrays helps in refining relationships and correlations because by essence they integrate rockmass heterogeneity (historical matching). Therefore monitoring from investigation and construction phase onward is needed for optimal follow-up during operation.

CONTAINMENT PRINCIPLE

The gas-tightness principle for underground LPG storage in mined caverns is based on **hydrodynamic containment** criteria: everywhere along the storage cavern wall and at any time during operation the groundwater flow is directed into the cavern, thus confining the stored product.

Despite the vicinity of aquifers or water bearing zones constituting strong boundary conditions, the variable hydraulic continuity in fractured rock, together with the low storativity of joints, often requires the implementation close to the storage caverns, of a so called **water curtain** system. This device allows to prevent rockmass desaturation during construction, and to ensure a stable, homogeneous potential distribution around the storage caverns under operation conditions.



INVESTIGATION, CONSTRUCTION AND COMMISSIONING

The overall understanding of the site geology and hydrogeology evolves following a continuous process from early investigation, through construction and well into cavern operation stage.

The geological, hydrogeological and geochemical data collected during the successive investigation campaigns, combined with the hydrological study of the catchment area, allow to elaborate hydrogeological conceptual and environmental models, which are used for designing optimised storage cavern facilities. However it is during construction that the most profitable testing and monitoring is possible, since the tests that can be carried out give full-scale investigation of the ground water flow in the cavern surrounding. This additional information allows refining the model and consequently to optimise the monitoring network for better appreciation of possible evolutions during operation. Furthermore during construction the underground works are at atmospheric pressure. The hydrogeological environment is therefore solicited at conditions more severe than the minimum operation pressure of the ultimate storage facility.

The construction phase consists of the access works (tunnel and shaft), the ancillary works (water curtain) and the underground storage caverns themselves. During each of these phases the overall hydrogeological environment is monitored thoroughly. This is done by piezometers, pressure cells, and water seepage & supply balance for the different sections of the underground works (see table). Further investigation is obtained from geological and geotechnical mapping, from probehole and grouting records, from additional investigation holes and water curtain borehole drilling, as well as from dye and/or interference tests.

During **construction** water curtain systems are implemented above and/or around the future storage locations. They consist of a set of permanently water-supplied boreholes. The quality of this supply water should be such as to avoid any adverse effect on the water curtain hydraulic efficiency (e.g. by clogging). It is also mentioned that one of the criteria during construction is that **no desaturation** is allowed in the zone below the water curtain system. A minimum pressure is to be maintained on the individual water curtain boreholes.

At particular stages during the construction works, **water curtain efficiency** tests are performed, aiming to check the hydraulic head in the rockmass. In the light of the results, local heterogeneous zones can be detected, then remedial actions can be implemented and adapted monitoring equipment can be installed.

Further, adequate **grouting** operations during the storage cavern excavation, help to reduce seepage and water curtain supply and to improve pore pressure distribution. Maximising grouting in the cavern reduces seepage for the operation phase, minimising grouting works in the water curtain system increases the water curtain efficiency. Decisions on grouting in access tunnel and shaft depend on water table stability, work progress and cost.

During **commissioning** a full-scale tightness test is carried out by pressurising the storage cavern with air. Large-scale hydrogeological analyses can be made, and the results refine the overall comprehension. During the tightness-test the hydrogeological environment is solicited at a pressure higher than the maximum operation pressure of the ultimate storage facility.

The different stages of the construction and commissioning allow for an optimised comprehension of the site. The situation occurring during construction with the underground works at atmospheric pressure, and the situation during the tightness-test with the test pressure higher than the ultimate operation pressure, both encompass the ultimate operation conditions and allow for adjustments if necessary.

Daily monitoring during storage operation is important to allow detection of possible deterioration of the containment criteria (ex. water curtain clogging). However, during **early operation**, water table recovery leads to transient operation conditions. They are a last step in the long learning process of the hydrogeological environment. The better a model is fitted during

the different stages of construction and early operation, the better the evolution during operation can be analysed and appreciated.

MONITORING DURING OPERATION

In order to establish an adequate hydrogeological monitoring for a storage facility, piezometric data have to be measured regularly, as well as all the parameters that may interfere directly or indirectly. Accordingly, the parameters to be monitored are related to storage operation, hydrogeological environment (hydraulic head distribution and chemical evolution) and water balance (natural and artificial supply and seepage water) (see table).

Cavern parameters : The basic operations of an underground storage facility are **product movements**, adding up to a continuously varying total **volume in stock**. The **temperature** of the stored product depends on its origin. When no product movement occurs within the storage cavern, the product temperature stabilises at the geothermal temperature. The combined effect of the total volume in stock and cavern temperature governs the wellhead **pressure**.

Parameters for the hydrogeological environment and confinement : The hydraulic head of the **water curtain system** is monitored, such as to allow to check both the hydraulic gradient and the hydraulic margin in the cavern vicinity.

The cyclic variation of cavern pressure during operation leads to hydrodynamic potential evolutions in a zone more or less important around the cavern. This influence is recorded by **nearby piezometers and pressure cells**.

Back ground data such as natural variation (ex. rainfall) or activities other than underground storage operation (ex. pumping for water resources, pumping or injection for civil engineering activities, or mining activities, ….) are to be monitored by an adequate **far-field piezometer** network and **climatic data**.

Parameters regarding water balance and its evolution : Further, two parameters regarding the water balance are monitored: the **seepage water** amount (seeping into the storage cavern) and the **water supply** quantities injected into the water curtain system. The evolution of the seepage water may indicate the evolution of the hydrogeological characteristics of the host rock or the cavern itself (clogging or declogging of grouted fissures, …). The evolution of the water supply into the water curtain system may be indicative of the evolution of the hydrogeological characteristics of the water curtain system, the host rock or the cavern itself (clogging or declogging of water curtain boreholes, or of fissures, …).

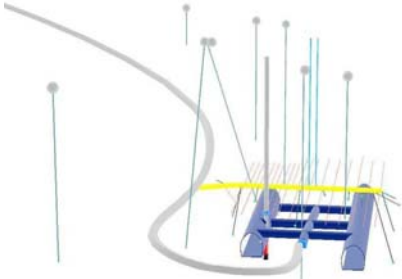
Chemical analyses and evolution : Chemical analysis of the water **seepage** into the cavern is needed to gain information on possible interactions with the rock formation and on possible changes in supply sources. Significant changes in seepage water composition generally point to important events, which may have an impact on the storage facility, and therefore have to be interpreted and accounted for.

The physical, chemical and bacteriological properties of water **injected** (or seepage water re-injected) into the water curtain is to be checked regularly. Bacteria development and high turbididity in the water curtain system should be avoided since this might lead to clogging of the water curtain system. Further, the physical and chemical compatibility between the injected water and the formation water is to be tested to ensure that the water curtain boreholes do not get clogged by precipitates.

Groundwater samples are taken regularly from **piezometers** for full chemical, physical and bacterial analysis. Also gas content is checked to confirm that there is no gas migration from the storage.

CONCLUSION

From monitoring and testing during site investigation a first hydrogeological model can be established. Monitoring results from the construction phase complete this model with a better understanding of the water table stability under heavy solicitations. The observations during construction also allow to identify, localise and characterise heterogeneities and/or singular features. Furthermore during the construction phase the cavern is at atmospheric pressure. The hydrogeological environment is therefore solicited at conditions more severe than the minimum operation pressure of the ultimate storage facility. On the other hand, during the tightness-test the hydrogeological environment is solicited at a pressure higher than the maximum operation pressure. Both situations encompass the ultimate operation conditions and allow for adjustments in case needed. During early operation, water table recovery leads to transient operation conditions. They are a last step in the long learning process of the hydrogeological environment, a knowledge so necessary for the optimal operation of underground LPG storage in unlined mined caverns where the tightness concept is based on the hydrodynamic containment principle.



		Before construction	**Construction**								**Storage cavern operation**
			Access tunnel excavation	Water curtain tunnel excavation	Storage cavern - top heading excavation	Water curtain efficiency test	Storage cavern – bench excavation	Full size water curtain test	Tunnel flooding	Tightness test & commissioning	
	Rainfall, effective rainfall, evapotranspiration, tide, …	x	x	x	x	x	x	x	x	x	x
Hydrogeological environment	Surface piezometers	x	x	x	x	x	x	x	x	x	x
	Chemical analyses for water samples	x	x	x	x	x	x	x	x	x	x
	Underground piezometers		x	x	x	x	x	x			
	Pressure cells			(x)	(x)	(x)	x	x	x	x	x
	Water curtain boreholes (flowrate & pressure)			x	x	x	x	x			
	Hydraulic head in water curtain								x	x	x
Water balance	Seepage water for access tunnel, water curtain, shaft, …		x	x	x	x	x	x			
	Seepage water for cavern				x	x	x	x	x	x	x
	Working water (water used underground for construction)		x	x	x	x	x	x			
	Water supply to water curtain			x	x	x	x	x	x	x	x
	Water supply to tunnel/shaft flooding								x	x	
Operation	Cavern pressure									x	x
	Gas volume in cavern									x	x
	Cavern temperature									x	x
	Gas liquid level in cavern									x	x

Hydrogeologic characterizations of a fractured crystalline rock site in Sweden based on intensive surface, borehole and subsurface investigations

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Despite intensive surface-based, borehole and tunnel investigations in heterogeneous fractured hard rock, an uncertain description of subsurface structures that conduct fluid may result. This is the case at a site in the Fennoscandian shield on the southeastern coast of Sweden. Data, collected by the Swedish Nuclear Fuel and Waste Management Co. (SKB), include geologic and geophysical properties, hydraulic response, and geochemical distributions. State-of-the-art characterization at the Äspö Hard Rock Laboratory (HRL) in Sweden provided a unique opportunity for detailed hydrogeologic characterization resulting in two detailed hydrogeologic structural models of a 2 km by 2 km by 1 km-deep block of crystalline basement. Some of the data were collected at the site of the underground Äspö Hard Rock Laboratory (HRL) prior to excavation of the laboratory. The initial model, based on this data, is compared with a model constructed with data collected in the tunnels following excavation. Although these models provide an intriguing view of the subsurface, comparisons with hydraulic data do not unambiguously confirm their power to describe hydrology. Further, it is not clear that surface-based measurements alone can provide a useful hydrogeologic structural model.

Initially, a structural model of the block was defined without reference to hydraulic or geochemical information using only pre-excavation data. Locations of fracture zones were hypothesized solely on the basis of surface and subsurface geologic and geophysical information, including borehole radar, resulting in a geologic structural model of the site comprising 52 fracture zones (Fig.1, left). Next, the structural model was evaluated for its ability to describe paths of subsurface fluid flow by spatial comparison of structure locations with locations of flows entering boreholes and by comparison of structure locations with pressure-propagation paths observed during transient hydraulic interference tests. The initial model appears to be a good descriptor of pressure propagation paths; however, it does not predict locations of subsurface fluid flow better than an arbitrary structural model containing random fracture zones with an equivalent spatial density.

Following excavation of the HRL, a second model (Fig.1, right), independent of the first one, was constructed from the subsurface data collected in the tunnels themselves. The second model considers tens of thousands of mapped intersections of structures with the tunnel. These intersections occur along several kilometers of HRL tunnels below the island of Äspö. Comparison of the surface-based and subsurface-based models shows that whereas data collected above ground gave some basis for a hydrogeologic structural model of this site, such a model must be refined significantly on the basis of information collected below ground in tunnels.

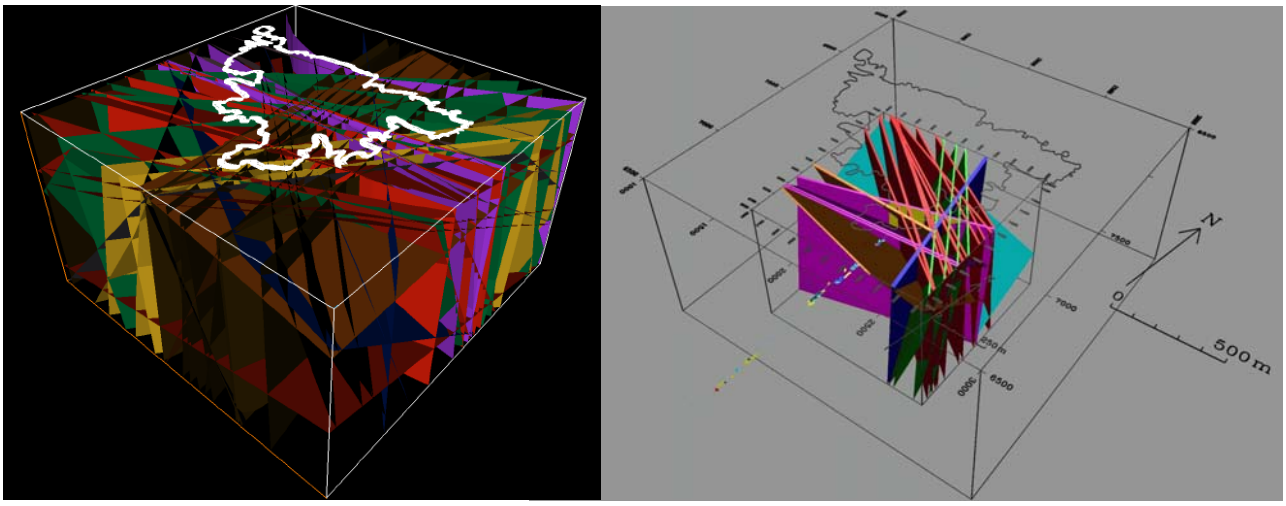

Figure 1. Surface-based (left) and subsurface-based (right) structural models of the island, Äspö, in Sweden

TOPIC 6

NUMERICAL MODELLING OF FRACTURED ENVIRONMENT

- Representative parameters as input data
- Modelling of groundwater flow and transport issues
- Continuum and discontinuum approaches, stochastic and deterministic treatment
- Model implementations

Determination of effective parameters for flow and transport in fractured porous media

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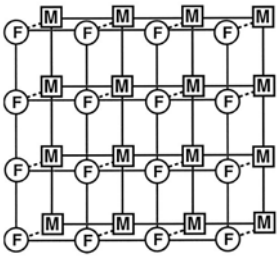
A b s t r a c t : The prediction of flow and transport behaviour in fractured porous media is very complicated due to their extremely heterogeneous structure. Therefore, the development of a practical tool to predict the groundwater flow and solute transport without knowing the exact geometry of the fractured porous media is required. To be applicable to engineering problems, this tool has to be as simple as possible and as exact as necessary by considering the characteristic flow and transport processes of the fractured porous media. For these specific reasons, a dual-permeability model based on a double continuum approach is a suitable method. In a first step a simplified two dimensional deterministic model of a local scale fracture network was used to investigate basic questions, such as the significance of advection within the permeable matrix and matrix diffusion on the general solute transport with respect to varying fracture and matrix parameter values. These investigations are the basis for the development of the double continuum model to describe the flow and transport processes in fractured porous media by effective parameters.

INTRODUCTION

Realistic fractures mostly form complex network geometries within a more or less permeable rock matrix. Whereas the fractures provide preferential pathways for fluid movement and solute transport, the rock matrix plays a primary role for fluid storage and retardation of contaminants. The large permeability difference between the fractures and the matrix as well as the complex geometries result in strong heterogeneous flow and transport patterns. As there is no possibility to obtain the detailed information of the fracture geometry and hydraulic properties in reality to describe the flow and transport patterns, a synthetic fracture network was used in the presented study. This synthetic fracture matrix system was created and simulated by the program package ROCKFLOW (Wollrath and Helmig 1991), using the finite element method.

ROCKFLOW enables to couple finite irregular elements of different dimensions to reproduce the geometry of fractured rock systems. This includes one-dimensional elements for preferential flow paths, two-dimensional elements for fractures and three-dimensional elements for matrix blocks. The finite element mesh generation can be done manually or by using the implemented mesh generator, which can refine the mesh near desired locations (static method) or at the locations with high hydraulic or concentration gradients (adaptive method). The flow calculation of the permeable porous matrix, which contributes to the overall flow, is based on Darcy's law. Within the fractures the flow regime can be calculated by the law of Hagen-Poiseuille for laminar or by the laws of Blasius or Nikuradse for turbulent flow in dependence of the hydraulic roughness. For transport modelling several processes can be applied to the model such as dispersion, sorption or sinks and sources.



F=Fracture, M=Matrix
(after Xu and Pruess 2001)

Figure 1. Double continuum approach

A double continuum model is a suitable approach to describe the heterogeneous flow and transport regime of fractured porous media without considering the details of geometry on a regional scale (Lang 1995). The fracture network as well as the rock matrix are treated as separated, but overlapping and interacting continua with different flow and transport parameters (fig.1). To identify these effective parameters of each continuum by inverse modelling, the discrete-fracture/permeable-matrix model will be used as a reference system due to its known properties (see Mohrlok 1996).

MODEL SETUP

For the numerical investigations on flow and transport within a saturated discrete-fracture/permeable-matrix system an idealized two-dimensional regular fracture network was set up. In this case the fractures were embedded as one-dimensional line elements in a two-dimensional matrix. This synthetic fractured porous medium contained two sets of fracture populations (fig.2). The fractures of each population were equidistant and possessed constant aperture values. The porous matrix blocks between them were defined as homogeneous and isotropic. On the in- and outflow boundary of the model a Dirichlet-boundary-condition was applied, which led in the presented case to a constant hydraulic gradient. The other two sides of the model were no-flow boundaries. For transport investigations a tracer concentration of 50 mg/L was added at the inflow cross-section continuously.

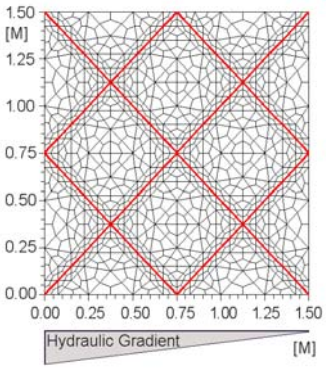


Figure 2. Fracture/matrix discretization

FIRST RESULTS

To analyse the effects of several parameter values on the flow and transport pattern of the synthetic fractured porous medium, a reference system with parameter values which are typical for granite rock were used (tab.1).

Table 1. Parameter of the reference system

Parameter	Value	Unit
matrix porosity	0.001	-
matrix permeability	10^{-9}	m/s
diffusion coefficient	10^{-10}	m^2/s
Dispersivities	$\alpha_l = 0.01$; $\alpha_t = 0.001$	m
hydraulic gradient	5	%
fracture aperture	0.001	m

As a result of the small matrix permeability the fractures dominated the global flow of the system. Due to the very high flow velocity difference and a small diffusion coefficient the fracture-matrix exchange was very low. For these reasons the tracer transport took place completely within the fractures, leading to a relative fast tracer breakthrough (fig.3). The longitudinal dispersion within the fracture network was small due to the regular fracture network and the fast tracer breakthrough.

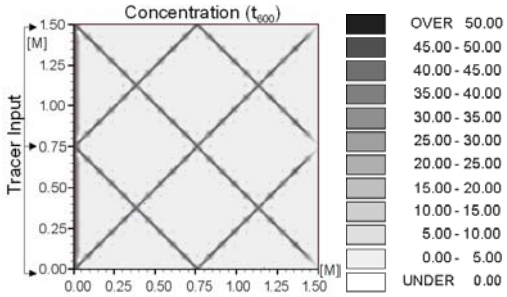


Figure 3. Reference flow and transport pattern

By increasing the matrix permeability to 10^{-5} m/s, the matrix contributed to the global flow leading to exchange processes between fractures and matrix blocks. Following the hydraulic gradient, the water entered the fractures from the left hand side and was leaving them on the right hand side additional to the fracture flow. In terms of transport this fracture-matrix exchange resulted in advective exchange processes (fig.4a). The global transport occurred within the fractures as well as in the matrix blocks. Due to the fracture-matrix exchange and the heterogeneous flow field within the system, the tracer concentration maximum front moved slower than for the reference system and was highly longitudinally dispersed.

The increase of the diffusion coefficient (10^{-6} m^2/s) by low matrix permeability led to a fracture-matrix exchange as well. This exchange process was not dependent on the hydraulic gradient, but strongly on the concentration difference between the fracture and the matrix. For this reason the tracer penetrated the matrix on both sides of the fracture, as long as the concentration within the fracture was higher then in the adjacent matrix blocks (fig.4b). In this case the matrix diffusion resulted in smaller longitudinal dispersion than the matrix advection, but it was significant higher than in the reference system.

If the tracer was added only to a part of the entire inflow cross-section, the plume became transversally dispersed due to the fracture network (fig.4c). At the fracture confluences, situated at the plume boundaries, the different tracer concentrations were flux weighted averaged by complete mixing. This dilution process led to a reduced tracer concentration maximum within the fractures in dependence of the distance from the tracer input and the number of mixing points. The additionally increased matrix diffusion also resulted in small longitudinal dispersion effects at the tracer front.

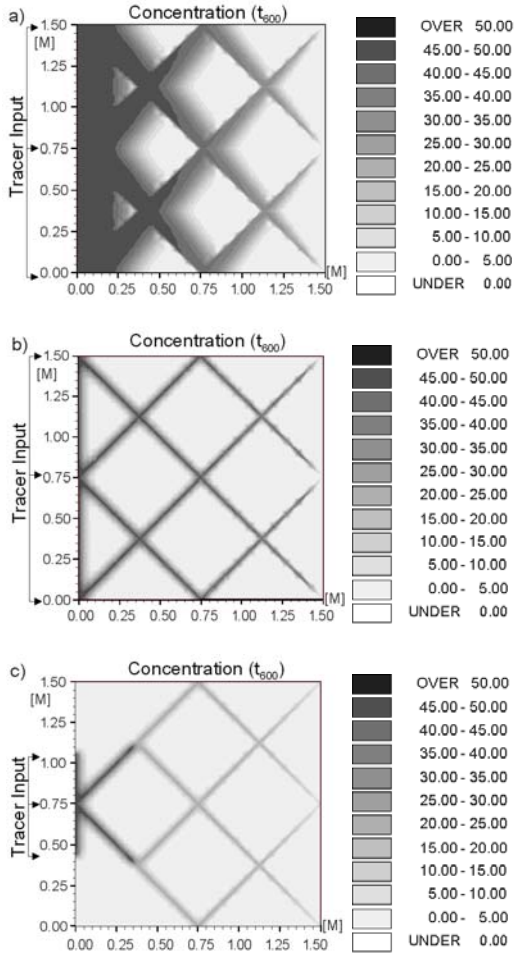


Figure 4. Effect of parameter value changes
a) matrix advection; b) matrix diffusion;
c) partial tracer input

OUTLOOK

To set up the double continuum model, further studies on the local scale fracture network model as well as on an extended regional scale model are necessary. In a next step the global flow and transport pattern of the double continuum model has to be adjusted to this of the discrete-fracture/permeable-matrix model by determining the parameter values of each continuum within realistic orders of magnitude. Of particular interest are the effective hydraulic conductivity and the effective dispersion coefficient.

REFERENCES

Lang U (1995) Simulation regionaler Strömungs- und Transportvorgänge in Karstaquiferen mit Hilfe des Doppelkontinuum-Ansatzes: Methodenentwicklung und Parameterstudie. Dissertation, Institut für Wasserbau, Universität Stuttgart (in german)

Mohrlok U (1996) Parameter-Identifikation in Doppel-Kontinuum-Modellen am Beispiel von Karstaquiferen. Dissertation, Tübinger geowissenschaftliche Arbeiten, C31 (in german)

Wollrath J, Helmig R (1991) SM-2/TM-2, Strömungs- und Transportmodell für inkompressible Fluide, Theorie und Benutzerhandbuch. Technical report Institut für Strömungsmechanik, Universität Hannover (in german)

Xu T, Pruess K (2001) Modeling multiphase non-isothermal fluid flow and reactive geochemical transport in variably saturated fractured rocks: 1. Methodology, American Journal of Science 301:16-33

MOPOD: A model to investigate fracture porosity development

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A b s t r a c t : A model (MOPOD) has been developed to investigate general relationships between simple fracture aperture growth laws and fracture porosity in fractured aquifers. The development of fractures has been studied where growth-rate is proportional to an exponent, *e*, of the flow rate through each fracture. The approach adopted is similar to that of statistical mechanical studies of simple systems, where evolved structures depend on the initial values. The evolved arrays show a range of diverse structures and geometrical phase changes as a function of the aperture growth-rate law and the initial aperture distribution, *i.e*. the standard deviation of the initial aperture distribution. Following an initial growth phase, during which dynamically stable aperture configurations develop, arrays undergo simple amplification. The evolved arrays are highly complex and parameterisation and prediction of their evolution in terms of the initial aperture distributions and growth-rate laws is not trivial.

CONTEXT OF THE STUDY

The spatial variability of flow and transport properties in fractured sedimentary aquifers can be greatly influenced by channelling of flow through preferentially enlarged components of the fracture network over a range of scales. There is a need to generate representative realisations of such fracture networks for use in flow and transport models particularly as it is difficult and costly to characterise fracture arrays in the field. The approach taken to modelling fractured aquifers is most commonly that of stochastic network modelling. Unfortunately, such models may not exhibit the long-range preferential pathways, associated with channelling of flow through fracture networks, which are important for contaminant transport (Berkowitz and Balberg 1993).

One approach to the generation of more realistic spatial correlations in fracture networks is to explicitly model the development of fractures according to fundamental physical and chemical laws (Bekri *et al*. 1977; Groves and Howard 1994; Dreybrodt 1996; Djik and Berkowitz 1998; Siemers and Dreybrodt 1998; Kaufman and Braun 1999). However, the idealised processes that are modelled, such as dissolution and precipitation, can grossly oversimplify the more complex field situation where hydromechanical plucking, abrasion and microbially mediated processes may be significant.

The work described here is a contribution to the endeavour of finding a middle-way between stochastic and process-based construction of fracture networks for flow and transport modelling, especially where a range of fracture modification processes are active. A particular aim of the study is to develop a generic model to investigate relationships between the growth of fracture apertures and the geometry of evolved fracture apertures using simple growth laws and simple fracture geometries.

THE MOPOD MODEL

The MOPOD model has been formulated as an 'initial value problem' expressed by a set of *N* first-order equations of the form $da_i(t)/dt = G(a_i, v_i, \mathbf{p})$, where $a_i(t)$ is the aperture of pore i (i = 1,…,N) at time t, subject to the initial aperture values, $a_i(0) = a_{i0}$, G is a user-defined function, **p** is a set of parameters, and v_i is the magnitude of the volumetric flow rate in pore i. For the model runs described in this paper aperture growth-rate was restricted to the form $da_i/dt = v_i^e$, where e is the aperture growth rate exponent.

The model is highly flexible. It is capable of modelling 2-D and 3-D arrays with both regular and random structures, a wide range of initial aperture distributions, and flexible boundary conditions including constant head or flow conditions. All simulations reported in this paper were performed on 20 by 20 arrays of fractures arranged on an orthogonal lattice with a constant unit flux condition across the lateral boundaries and a no-flow condition at the upper and lower boundaries. Also, the flow rates were restricted to being proportional to the cube of the aperture ('cubic law') and to the head gradient (Darcy's law).

We chose to work with the statistics of the logarithms of the apertures, $z_i = \log_{10} a_i$. All the model runs described here used initial aperture distributions that were spatially un-correlated and lognormal. We denote the initial mean and standard deviation of the z_i values by μ_z and σ_z, respectively: unless otherwise stated, the geometric mean of the initial, a_{i0}, values was set to unity (equivalent to $\mu_z = 0$).

Model runs were performed to investigate the effects of changing the growth-rate exponent, e, and the width of the initial aperture distribution, σ_z. The aperture growth-rate exponent was investigated in the range 0.1 to 0.8. The width of the initial distribution was varied in the range σ_z = 0.1 to 0.7.

RESULTS

A range of qualitatively distinct evolved geometries can be recognised as a function of the growth-rate laws and the width of the initial aperture distribution. At low growth-rate exponents ($e \leq 0.3$) and moderate values of σ_z ($\sigma_z < 0.4$), there is a homogenisation of apertures oriented parallel to the head gradient with model time. At moderate growth-rate exponents ($0.3 < e < 0.6$) row apertures become increasingly heterogeneous in the evolved arrays, planar heterogeneities develop parallel to the head gradient for low values of σ_z while anastomosing structures develop at higher σ_z values. For growth-rate exponents in the range $0.6 < e < 0.8$ preferentially enlarged array-spanning paths develop. When both e and σ_z are large the array-spanning structures no longer develop, instead isolated enlarged apertures develop. The range of evolved structures is illustrated schematically in Fig.1. Only significantly enlarged components of the orthogonal fracture array are illustrated. Limited additional modelling has shown that similar trends in the geometry of developing arrays can be generated by varying the initial mean (log) aperture, μ_z. For example, smaller values of μ_z lead to the promotion of single array-spanning structures, while higher values of μ_z tend to lead to more homogeneous apertures parallel to the head gradient.

The fracture aperture distributions appear to become dynamically stable with model time. This is illustrated in Fig.2, which presents nine aperture maps based on $\sigma_z = 0.3$ and $e = 0.5$. The maps in the left-hand column of the figure are the full fracture aperture maps for arrays at model times t = 0, 10, and 40. The centre and right-hand columns show only the largest 25% and 10% of apertures, respectively. At an early stage in the evolution of the array, the largest apertures are distributed throughout the array with both row- and column-parallel orientations. As the array develops the largest fracture apertures form more continuous structures aligned with the head gradient (left to right), which, at higher aperture growth-rate exponents,

lead to the development of the preferentially enlarged array-spanning paths. Formation of dynamically stable aperture distributions appears to correspond with re-organisation of the largest fracture apertures at early times in the development of the arrays. Once the stable configuration has developed the aperture field is simply amplified following the aperture growth law. Limited additional modelling, taking evolved apertures arrays as the starting point for new growth models, suggests that changes in growth-rate exponent at later stages only acts to intensify structures already developed.

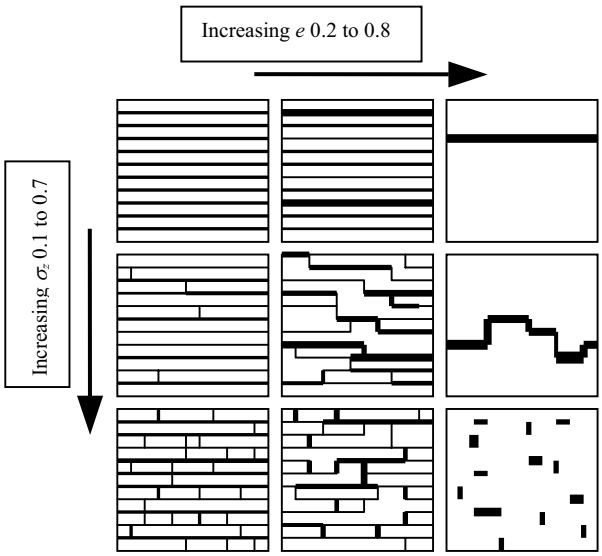

Figure 1. Schematic illustration of the geometry of evolved fracture arrays a function of e and σ_z. Only significantly enlarged components of the fracture array are illustrated.

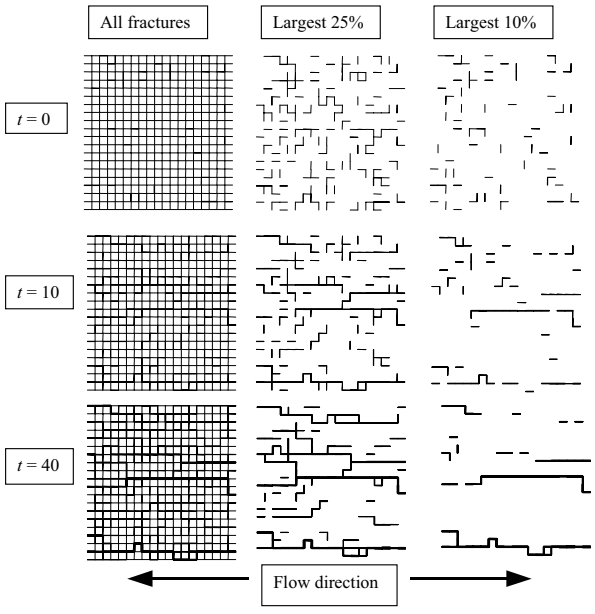

Figure 2. Fracture aperture maps illustrating the development of dynamically stable fracture porosity (see text for details).

DISCUSSION

Many of the evolved MOPOD structures exhibit similar geometries to those developed using dissolutional growth to model karst formation and development in fractured carbonate rocks. There is, however, a fundamental difference between the manner in which porosity develops in the MOPOD model and process-based models. The model is configured so that it is always in a quasi-steady-state of flow and, since aperture growth depend on the magnitude of the flux not its direction, model runs (using identical initial aperture distributions) with the same head gradients or fluxes from left to right and from right to left, develop identical evolved aperture arrays. There is no tracking of 'packets' of water through the model. Consequently, MOPOD develops fracture porosity, including the preferentially enlarged array-spanning structures, without propagation of dissolutional fronts under chemical gradients. Instead fracture porosity develops in response to local flow conditions controlled by the aperture field distribution and a (remote) macroscopic head gradient.

A number of approaches have been explored in an attempt to characterise the arrays. Basic visualisation enables a qualitative description of the range of evolved structures, statistics provide quantitative descriptions of the arrays and variograms can be used to characterise the development of spatial correlation in the aperture field. The development of correlations in flow rates between adjacent fractures can also be tracked by comparing the maximum flow into and out of a fracture intersection: increasing correlation in maximum inflow and outflow with time is a characteristic feature of array development. More rigorous parameterisation of the evolving arrays is far more problematic. It has not been possible to identify parameters that can be used either to predict the form of the evolved arrays on the basis of the initial aperture distributions or growth-rate laws.

Analytical solutions to the head and flow equations on some very small arrays consisting of two to five fractures have been developed to predict aperture growth. The analytical model revealed critical exponents. Depending on the geometry, systems with more than about five fractures gave rise to complicated coupled non-linear equations that could not be solved analytically. Consequently, although the simple analytical models may reproduce many of the characteristics of the MOPOD model, they are of limited use.

CONCLUSIONS

A simple model, based on a limited number of assumptions and on simple growth laws applied to idealised fracture arrays with simple initial aperture distributions, can be used to generate long-range correlations (array-spanning paths) in enlarged fracture arrays. In that context, it holds the potential to replicate natural fracture arrays and so be useful in the generation of fracture templates for flow and transport modelling.

REFERENCES

Berkowitz B, Balberg I (1993) Percolation theory and its application to groundwater hydrology. Water Resources Research 29:775-794

Bekri S, Thovert J-F, Adler PM (1979) Dissolution and deposition in fractures. Engineering Geology 48:283-308

Dijk P, Berkowitz B (1998) Precipitation and dissolution of reactive solutes in fractures. Water Resources Research 34:457-470

Dreybrodt W (1996) Principles of early development of karst conduits under natural and man-made conditions revealed by mathematical analysis of numerical models. Water Resources Research 32:2923-2935

Groves CG, Howard AD (1994) Early development of karst systems. 1. Preferential flow path enlargement under laminar flow, Water Resources Research 30:2837-2846

Kaufmann G, Braun J (1999) Karst aquifer evolution in fractured rocks. Water Resources Research 35:3223-3238

Siemers J, Dreybrodt W (1998) Early development of karst aquifers on percolation networks of fractures in limestones. Water Resources Research 34:409-419

Coupled hydro-mechanical modelling of flow in fractured rock

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A b s t r a c t : Using fracture data from Sellafield, UK, a modelling-based approach to characterising the contribution of hydro-mechanical processes to large scale flow and transport reveals three important hydrogeological issues for the performance assessment of a repository host rock. First, inference of the statistical model of fracture length distribution using power law distribution models can lead to large uncertainty in fracture density. Second, fracture length is less important than fracture density in determining the flow characteristics of the rock mass. Third, the depth dependence of permeability can be isolated using hydro-mechanical models but the major uncertainty in the analysis is the characterisation of the rock mass mechanical properties.

INTRODUCTION

A numerical approach to quantifying the importance of hydro-mechanical (HM) processes in fractured rock to large-scale radionuclide migration through a repository host rock has been developed (fig.1) and tested. Statistical models of fracture set properties, inferred from measurements, are used to generate multiple realisations of discrete fracture networks (DFN) that can be inputed to numerical models to explore the relationship of the hydraulic properties to the in-situ stress conditions. The uncertainties inherent in the identification of the statistical parameters for the DFN from the fracture data are considered explicitly in the analysis of the local scale behaviour of the fractured rock. Two numerical codes have been coupled to explore the hydro-mechanical interactions between flow and stress patterns. The universal distinct element code, UDEC-BB, incorporating the Barton-Bandis model for fracture stress and strain is used to determine the HM contributions to fracture aperture distributions and the fracture flow code, FRAC2D, is used to calculate the flows across the stress-modified DFN. In the final stage the local scale hydraulic properties are upscaled for input to a large-scale continuum model. The methodology has been applied using data from the Sellafield (UK) site investigation programme performed by United Kingdom Nirex Limited and provided as part of the second Bench Mark Test (BMT2) of the international collaborative programme DECOVALEX III. The modelling was carried out in two dimensions (2D) to constrain the computational effort. A 2D model plane orientated along the main horizontal stress direction (159/339º) observed at Sellafield was adopted for the BMT2.

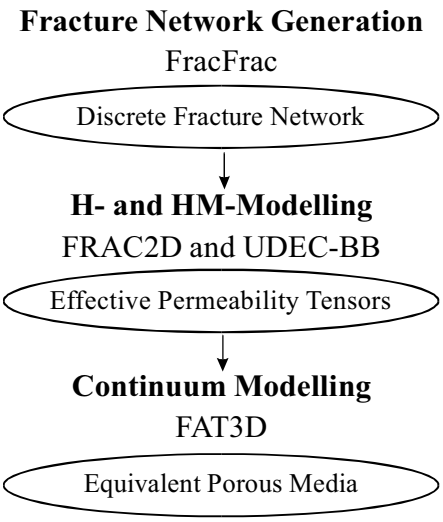

Figure 1. Stages used to quantify HM contributions to fractured rock hydraulic behaviour at large scales.

DISCRETE FRACTURE NETWORK-ANALYSIS

Three rock formations are identified in the data set and the given 3D discontinuity data of the fracture orientation and the fracture spacing were transformed into equivalent 2D data (tab.1). Analysis of the fracture data for the repository host rock indicates that a power-law fracture length distribution for the four fracture sets can describe the fracture network characteristics in 2D. The power-law distribution of the fracture length is given by:

$$N_F = CL^{-D} \qquad (1)$$

where N_F is the number of fractures per unit area of fracture length greater than the length L, C is the density constant and D is the fractal dimension (fig.2). Only fractures with a length greater than 0.5 m were recorded, therefore 0.5 m was chosen as the lower-cut of length of the power-law. The lower-cut off length defines the fracture intensity (P_{20}, Dershowitz 1984) for given values of C and D. For the data, values of C and D of 4.00 and 2.20 respectively are presented in Nirex (1997b), which result in a relatively high fracture intensity of 18.4 m^{-2} (high-density case in figs. 2 and 3). Analysis shows that these values are representative of one part of the available data but not all. The best fit using all the data suggests a density constant of 3.23 and a fractal dimension of 2.08 yielding a fracture intensity of 13.7 m^{-2} (median-density case in figs. 2 and 3). A further data set with an average fracture intensity of 4.8 m^{-2} is also identified in Nirex (1997b). An equivalent power-law length distribution for this low fracture intensity was obtained by a visual fit to the full data and gave values of C and D of 1.20 and 2.00 (low-density case in figs. 2 and 3). This analysis of the fracture length and fracture density data shows significant variations in fracture density, depending on the sample data used even though the data are from the same site. A sensitivity study using the three fracture densities (low-, median- and high-density cases) has been undertaken. Bonnet *et al*. (2001) provides a review of modelling DFN with a power-law distribution and guidance on the use of the power-law model.

Table 1. Discontinuity data (data from Nirex 1997a).

Rock Unit	Set	DD	α	β	S_t [m]	S_a [m]
For-mation 1	1	145	8	7.8	0.29	0.29
	2	148	88	88.0	0.26	0.25
	3	21	76	71.5	0.28	0.19
	4*	87	69	38.8	0.31	0.14
For-mation 2	1	28	25	17.0	0.51	0.49
	2	156	81	81.0	0.35	0.35
	3	20	72	66.7	0.28	0.19
	4*	90	68	41.6	0.41	0.21
Fault Zone	1	21	8	6.0	0.18	0.18
	2	150	76	75.8	0.18	0.18
	3	21	72	66.4	0.19	0.13
	4*	85	74	43.9	0.22	0.08

DD=dip direction, α=true dip, β=apparent dip, S_t=mean true spacing, S_a=mean apparent spacing, * neglected fracture set.

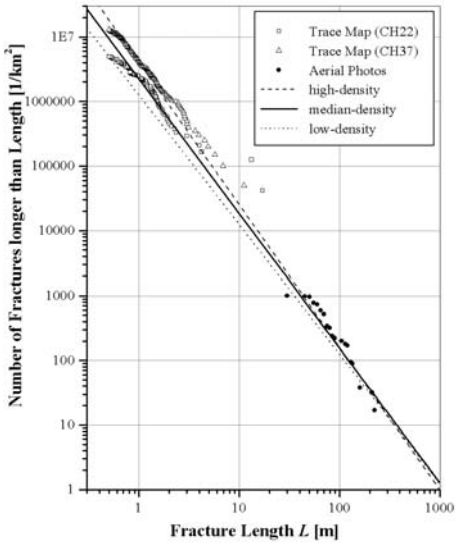

Figure 2. Power-law fracture length distribution (data from Nirex 1997b)

Fracture Network Generation

A fracture network generator (FracFrac) was developed to generate DFN with a power-law length distribution. For each formation only three fracture sets have been used to develop the 2D models (Tab.1), because the fourth steeply dipping fracture sets in each formation possess almost the same strike as the model plane. A Poisson distribution has been assumed for the fracture midpoints, although analysis suggests the existence of a repulsion between long fractures. The dispersion of the fracture orientation is described with the Fisher distribution and a constant K ranging from 5.9 to 13.0, which indicates a fairly high dispersion of the fracture orientations. Visual comparisons of DFN generated with the Fisher distribution and the trace maps clearly indicate that a high dispersion of orientation does not produce synthetic networks that are comparable to those observed. It is apparent that fracture orientation dispersion is length dependent with low dispersion of longer fractures and higher dispersion of shorter fractures. Wu & Pollard (2002) have also observed a decrease in the deviation of the fracture orientations within a fracture set as the fracture length increases. Hydraulic modelling ignoring mechanical stresses using DFN with the median fracture density (P_{21} = 13.2 m/m^2) shows, that due to the relatively high fracture density the impact of the repulsion and the dispersion of the fracture orientation has only a minor impact on the equivalent large scale continuum hydraulic properties for this case (Chillingworth 2002).

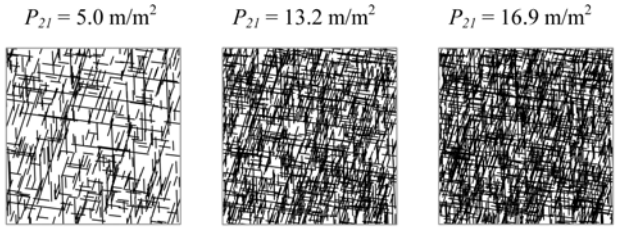

Figure 3. DFN showing fracture distributions for the low-, median- and high density cases of Formation 1. Region size = 10 m × 10 m.

HYDRAULIC ANALYSIS

Constant aperture hydraulic (H) modelling was undertaken initially to determine the minimum size of model region required to approximate a REV (representative elementary volume) Several methods exist to evaluate the 2D permeability tensor in fractured rock (e.g. Zhang and Sanderson 2002). In this study the evaluation is based on the approach of Jackson *et al.* (2000), which uses several hydraulic boundary conditions corresponding with a uniform head gradient in different orientations. A guard zone is maintained around the model region to reduce edge effects. For the hydraulic analysis a constant hydraulic aperture was adopted (a_h = 130.7 µm). One hundred simulations for each model region were performed and the permeability tensor coefficients were evaluated using a maximum likelihood approach. Simulations were conducted on square model regions from 5-100 m side length for each of the fracture density cases.

REV-Analysis

An REV-criteria was set, that when the cumulative variances of the permeability tensor coefficients and the principal directions with increasing domain size are all less than 5 % of their cumulative averages, then the model region is assumed to be larger than the size of the REV. The results showed that for the median- and high-density cases a model region of 10 m × 10 m is adequate for modelling. However for the low-density no REV was identified. This is apparently due to the decrease of connectivity in the minor flow direction for this model, which is demonstrated by the changing in principal directions towards higher angular values with increasing domain sizes.

HYDRO-MECHANICAL ANALYSIS

The HM-modelling has been performed with the UDEC-BB model with aperture distributions output to FRAC2D for the hydraulic calculations. Only median-density DFN have been analysed to date. The HM modelling has been carried out in a similar manner to the H modelling with the inclusion of a guard zone to minimise edge effects. Sensitivity studies have been carried out to examine the impact of the mechanical boundary condition, mechanical properties, initial mechanical apertures, aperture changes with increasing depth (HM-coupling) and various DFN with changing fracture lengths and block sizes. The two main conclusions of the HM-modelling are presented here. First, the variation of hydraulic properties as a function of depth can be identified using this modelling method with given mechanical properties and fracture geometries. Significant differences between the constant aperture H modelling and variable aperture HM modelling results are observed that lead to different large scale flow conditions. Second, the sensitivity studies revealed that the underlying variation in the mechanical properties have a significant impact on the HM-modelling. Understanding the spatial variation of the mechanical properties of the rock mass and fractures is vital to understand the connectivity of high and low permeability zones and to model the heterogeneity of the host rock at the large scale.

REFERENCES

Bonnet E, Bour O, Odling NE, Davy P, Main I, Cowie P, Berkowitz B (2001) Scaling of fracture systems in geological media. Reviews of Geophysics 39(3):347-383

Chillingworth GEH (2002) The Effects of Fracture Geometry on the Permeability of Fractured Rock. Unpublished MSc-Thesis, Department of Earth Sciences, University of Birmingham, UK

Dershowitz W (1984) Rock Joint Systems. PhD-Thesis, Massachusetts Institute of Technology, Cambridge, Massachusetts

Jackson CP, Hoch AR, Todman S (2000) Self-consistency of a heterogeneous continuum porous medium representation of fractured media. Water Resources Research 36(1):189-202

Nirex (1997a) Data summary sheets in support of gross geotechnical predictions. Nirex Report SA/97/052, Harwell

Nirex (1997b) Evaluation of heterogeneity and scaling of fractures in the Borrowdale Volcanic Group in the Sellafield area. Nirex Report SA/97/028, Harwell

Wu H, Pollard DD (2002) Imaging 3-D fracture networks around boreholes. AAPG Bulletin 86(4):593-604

Zhang X, Sanderson DJ (2002) Numerical Modelling and Analysis of Fluid Flow and Deformation of Fractured Rock, 1st edition. Pergamon, Amsterdam, 288 pp

Modelling groundwater flow in an elastic confined aquifer

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A b s t r a c t : The paper discusses a dynamical three-dimensional numerical model for groundwater flow through a porous medium that may deform non-linearly and its application to elastic and inelastic deformations in porous and fractured aquifers. The model is based on the concept that the porous medium consists of three interacting species, soil, water and air, the behaviour of which is governed by the classical laws of conservation of mass and Newton's second law of motion. Numerical simulations performed with the model indicate that the pumping of a borehole that intersects a horizontal fracture generates oscillations in the surrounding rock matrix with amplitudes that increase exponentially with the discharge rate. A very important result derived from the model is that the specific storativity and hydraulic conductivity of an aquifer are functions of the amplitudes of the matrix deformations, and therefore functions of the discharge rate of the borehole and not independent parameters as assumed normally.

INTRODUCTION

A previous investigation of the Karoo aquifers of South Africa (Botha *et al.* 1998) have shown that boreholes drilled into the aquifers only have significant yields if they intersect a horizontal bedding-parallel fracture. However, the pumping of such a borehole could cause a significant deformation of the borehole and aquifer, as illustrated in fig.1. This observation suggested that aquifer deformations might play a very significant part in the behaviour of Karoo aquifers and boreholes drilled into the aquifers. Since the authors were not aware of equipment that could be used, in a field study of the influence that aquifer deformations may have on the behaviour of an aquifer and borehole, it was decided to use a numerical model instead.

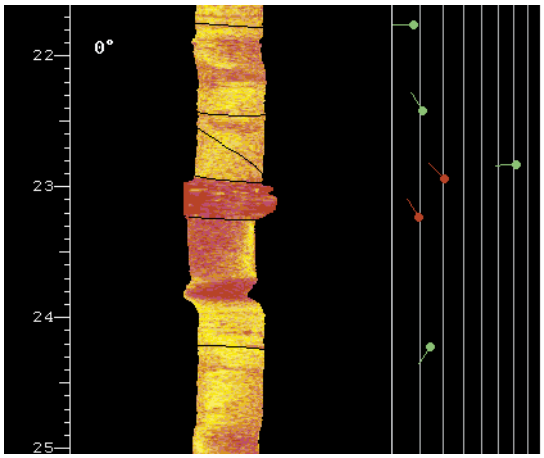

Figure 1. Acoustic scanner image of deformations in borehole UO5 on the Campus of the University of the Free State

DISCUSSION

The first and most unexpected result obtained with the model is the dependence of the drawdowns on the position in the aquifer. In the fracture, its immediate neighbourhood and the region below it, the drawdowns increase steadily with time, as expected. However, there is a region, centred at approximately 800 mm above the fracture, where the simulated drawdowns decrease with time, after the pump was switched on, before the drawdown began to increase with time, see fig.2. This behaviour may serve as a numerical illustration of the somewhat paradoxal phenomenon, often observed during hydraulic tests of Karoo boreholes that the water level in an observation borehole begins to rise the moment the pump is switched on in the production borehole (Botha *et al.*, 1998). Since it is impossible to explain this phenomenon in the conventional theory of groundwater flow, its existence must be attributed to the deformation of the rock matrix in the deformation model, caused by the pumping of the borehole.

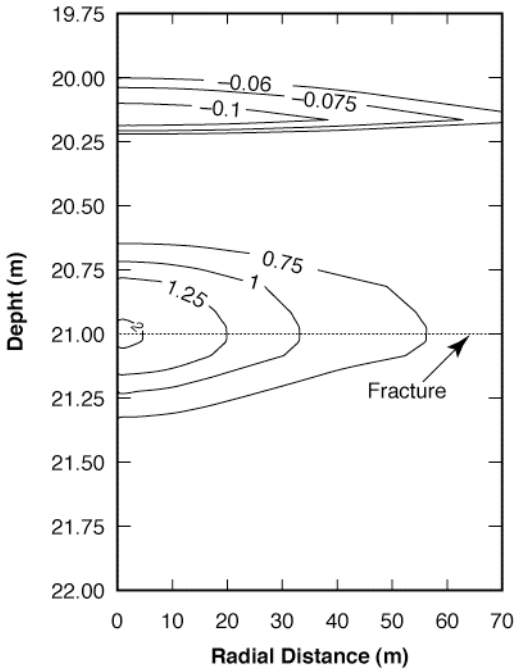

Figure 2. Contour map of simulated drawdowns in the rock matrix of the aquifer used in the model after pumping a borehole for 45 s

The fact that the pumping of a borehole can generate deformations in an aquifer, with magnitudes that increase with the discharge rate of the borehole, obviously has very important consequences for groundwater resources. Two sets of numerical experiments were therefore performed with the model, one with the linear form of the model and the other with the non-linear form. Very little difference was observed between the displacements computed with the two forms of the model for a discharge rate $Q = 1{,}4\ m^3/h$ over a period of approximately 500 minutes. However, the situation changed drastically, when the discharge rate was increased. The drawdowns and displacements in the linear model increased smoothly with the discharge rate, but began to oscillate violently in the non-linear model, with magnitudes that increased with time, which changed the fracture from a flat horizontal plane into a non-linear wave-like surface. Since non-linear deformations do not restore a body to its original form once the deforming force is removed, but creates so-called

residual deformations, such deformations could have disastrous consequences for an aquifer if not taken care of.

The formation of residual deformations is particularly important for Karoo aquifers, since they may ultimately constrict the aperture of a bedding-parallel fracture completely. This phenomenon is illustrated in fig.3, which displays the constriction experienced by a 50 mm thick slice of the aquifer centred on the position of the fracture in the model. Residual deformations could therefore have important implications for the management and life expectancy of a given borehole, because it will cause irreversible structural damages to the porous matrix surrounding a borehole and even the borehole itself, as illustrated in fig.1.

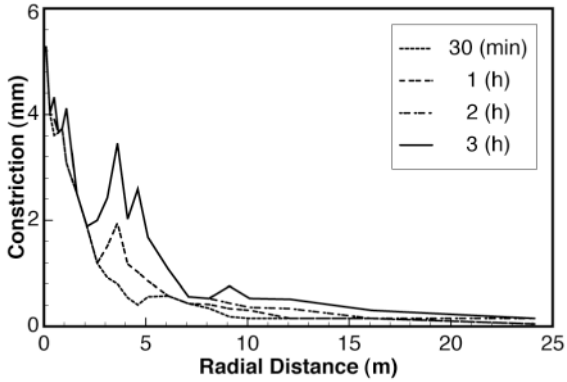

Figure 3. Variations of the simulated constrictions in the aperture of the fracture in the Campus Test Site model at various times during the period that the borehole was pumped at a rate Q = 4,1 m^3/h as functions of the radial distance

It is important to note that the constrictions in fig.3 developed very quickly at early times of pumping and then approach a pseudo steady state within approximately two hours of pumping. This behaviour and the observation of (Botha *et al.* 1998) that a borehole in a Karoo aquifer will only yield water if it intersects a horizontal fracture, suggest that boreholes in these aquifers may have a limited expected mechanical life, defined as the time it will take residual constrictions to reduce the aperture of the fracture to zero. This conclusion is fully supported by the simulations. These simulations indicated that the borehole in the model will fail in less than six years, if pumped at a rate of 8,3 m^3/h for 8 h a day, every day of the year, but that it will suffer no significant mechanical damages, if the discharge rate is kept at or below 1,4 m^3/h. The mechanical properties of a fractured aquifer may therefore be as important as its hydraulic properties in designing a discharge rate for a production borehole. It is therefore important that more attention should be paid to the mechanical properties of the aquifer in the management and control of well fields, especially those based on fractured aquifers.

A major characteristic of the simulated displacements and associated strains is that their magnitudes decrease exponentially with distance from the borehole, similar to the constrictions in fig.3. This behaviour implies that the dilatational strain, which is the real physical mechanism controlling the release of water from an aquifer (Botha and Cloot 2002), must also decrease with distance from the borehole. One would therefore expect that the two parameters—specific storativity and storativity, commonly used in the conventional theory of groundwater flow as a measure of the release of water from an aquifer, should be inversely related to the distance from the borehole. The decrease in the values of S with distance from the pumped borehole, observed by Bredenkamp *et al.* (1995) and Botha *et al.* (1998), see fig.4, is therefore not an artefact of the methods used in the analysis of the tests, but a physical reality!

No attempt was made in the present investigation to relate the deformations and hydraulic conductivity, K, of an aquifer. However, it is worth noticing that K, which describes the ease with which water flows through the rock matrix, is related to the permeability tensor, k, of the rock matrix (Bear 1972; Botha 1996). The permeability could therefore be interpreted as a parameter that describes the extent to which the roughness and tortuosity of the rock matrix obstructs the flow of groundwater. Since deformations will obviously have an influence on the roughness and tortuosity of the rock matrix, the dependence of the transmissivity on distance, observed by (Botha *et al.* 1998), may be an indication that k (thus K) also depends on the deformations. This dependence of the specific storativity and k on the deformation of an aquifer could explain why the storativities and transmissivities of aquifers, determined from conventional hydraulic tests, are not independent parameters as they should be from both the mathematical and the physical point of view. This raises the question: to what extent are the variations observed in hydraulic parameters derived from hydraulic tests affected by variations in the discharge rates of boreholes used in these tests instead of the heterogeneity of the aquifer, as commonly assumed?

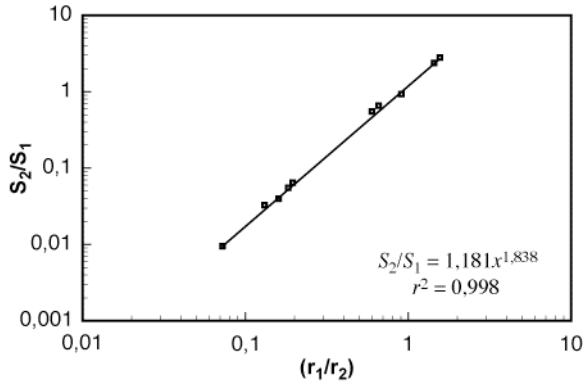

Figure 4. Dependence of the Theis-fitted S-value ratios on the inverse ratio of the distance between an observation borehole and the pumped borehole as determined from two constant rate tests performed on the same two boreholes at the Campus of the University of the Free State (Botha *et al.* 1998)

REFERENCES

Bear J (1972) Dynamics of Fluids in Porous Media. American Elsevier Environmental Science Series. American Elsevier Publishing Company, Inc, New York

Botha JF (1996) Principles of Groundwater Motion. Unpublished Lecture Notes. Institute for Groundwater Studies, University of the Orange Free State, PO Box 339, Bloemfontein 9300

Botha JF, Cloot AHJ (2002) Karoo Aquifers. Deformations, Hydraulic and Mechanical Properties. Draft Report on the Project: Flow and Transport Characteristics of Groundwater in Karoo Formations. Water Research Commission, PO. Box 824, Pretoria 0001

Botha JF, Verwey JP, Van der Voort I, Vivier JJP, Buys J, Colliston WP, Loock JC (1998) Karoo Aquifers. Their Geology, Geometry and Physical Behaviour. WRC Report No 487/1/98. Water Research Commission, PO Box 824, Pretoria 0001

Bredenkamp DB, Botha LJ, Van Tonder GJ, Janse van Rensburg HJ (1995) Manual on Quantitative Estimation of Groundwater Recharge a*f*nd Aquifer Storativity. WRC Report No TT 73/95. Water Research Commission, PO Box 824, Pretoria 0001

Anomalous diffusion in regular fractured media

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A b s t r a c t : The idea of anomalous diffusion mechanism in a medium with a single fracture is applied to different types of fractured media. An anomalous regime is found to take place in all of them.

Contaminant transport in regular heterogeneous media consisting of narrow areas ("fractures") with diffusivity D and a matrix with the diffusivity d (D being much greater than d) has been analyzed. Considered are the systems of two and of an infinite number of parallel flat and cylindrical inclusions (henceforth we call them "fractures" for brevity), and an "interconnection" of two semi-infinite flat parallel fractures, coming close to each other ("gappy fracture"). For single fractures, as it had been found in Dykhne *et al.* (2002), in the time range of $t_1 << t << t_2$ (where $t_1 = a^2/4d$, a is a characteristic dimension of fracture cross-section, $t_2 = (D/d)^2 t_1$ for flat fractures and $t_2 = (D/d)\ln\{(D/d)t_1\}$ for cylinder ones) the contaminant transport is of subdiffusion behavior with dispersion $\sim D\sqrt{tt_1}$ for flat and $\sim Dt_1 \ln(t/t_1)$ for cylindrical fracture; in the time ranges $t << t_1$ and $t >> t_2$ classical diffusion takes place with effective diffusivities D and d, respectively.

For all fracture systems analyzed here: there has always been found to exist a time interval (its duration being in the majority of cases monotonic with D/d), within which the system is in a subdiffusion mode (SDM).

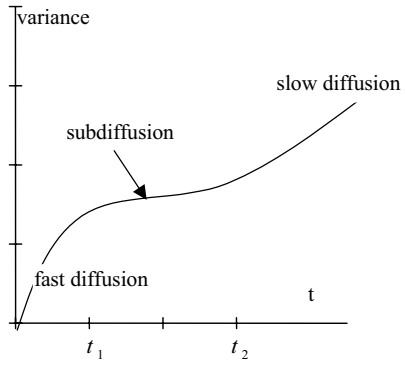

Figure 1. Scheme of dispersion-time dependence for an infinite sequence or a pair of flat fractures at $b >> a(D/d)$ and for a set of cylindrical parallel and uniformly distributed in space fractures or a pair them at $b >> a\sqrt{D/d}$. The scheme is also relevant to dispersion in a chain-like cylinder fracture system when $b >> a\sqrt{D/d}$

Namely, gappy fracture with a gap of b width, as well as all other mentioned above fracture sets with b-distanced fractures, enter into subdiffusion regime at $t \sim t_1$ (figs.1,2,3) (at smaller times the dispersion is proportional to Dt). The further behavior depends on the relation between t_2 and the diffusion time through space between fractures $t_b \equiv b^2/4d$: if $t_2 << t_b$, the system leaves the SDM before fractures can act collectively, and after t_2 the diffusion obeys conventional (linear) laws with averaged over the space diffusivities (fig.1). If, otherwise, $t_1 << t_b << t_2$, then after t_b cooperation occurs and the cease-time t_c of SDM is determined by the logic of this collective behaviour. Particularly, $t_c = t_2$ (fig.2) for two parallel flat fractures, for a gappy fracture and for a chain-like parallel-cylinder fracture system (in the latter case at t_b the subdiffusion switches from logarithmic to square-root type), and $t_c = \frac{a^2}{d}\frac{D}{d}\ln\left\{(a/b)\sqrt{D/d}\right\}$ for two parallel cylindrical fractures. For the considered infinite sets of parallel fractures, uniformly distributed in space $t_c = t_b$ (fig.3).

For the two parallel flat fractures at $t >> t_b$ the Fourier-Laplace component of the concentration integrated over fractures width $N_{ks} = \sum_j \int_{j^{th}\,fracture} n_{ks}^{(j)} dz$ obeys the relation $\left[s + \left(d + \frac{2a}{b}D\right)k^2 + \sqrt{\frac{s+dk^2}{t_b}}\right] N_{ks} = const$, from which follows the contaminant variance $4\left[\left(d + \frac{2a}{b}D\right)\sqrt{\pi t_b t} + dt\right]$.

Here k and s are Fourier and Laplace variables. For the staircase of flat fractures the corresponding expressions are $\left[s + \left(d + \frac{a}{b}D\right)k^2\right] N_{ks} = const$ for N_{ks} and $4\left(d + \frac{a}{b}D\right)t$ for the variance.

When the ratio D/d (or b/a) is extremely large (e.g., in case of rock fractures), the time t_c might practically not be accessible resulting in that the regime of anomalous diffusion (subdiffusion) becomes asymptotic. Therefore, in connection with contaminant transport in fractured rocks, we may deal with the effect of suppression of the dispersion in fractures. Fracture "interconnections" are found to be inessential for complex systems diffusion time-patterns. The results obtained may be helpful for the development of methods to assess reliability of radioactive waste storage in rock massifs.

REFERENCES

Dykhne AM, Dranikov IL, Kondratenko PS, Popov AV (2002) Anomalous diffusion in regularly non-uniform media. In: Findikakis A (ed) Bridging the gap between measurement and modeling heterogeneous media - Proc International Groundwater Symposium 2002:408-411

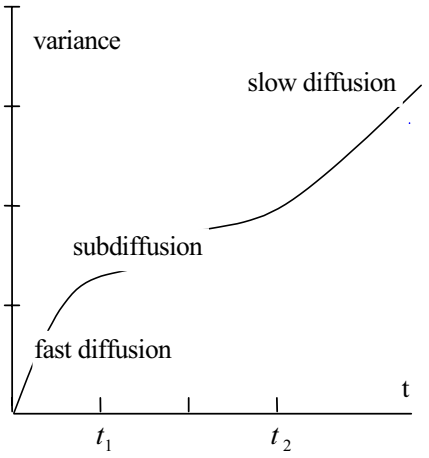

Figure 2. Scheme of dispersion-time dependence for two parallel flat fractures in case $b << a(D/d)$ and for two parallel cylindrical fractures in case $b << a\sqrt{D/d}$ (here t_2 must be replaced by $(a^2/d)(D/d)\ln\{(a/b)\sqrt{D/d}\}$). The scheme is also relevant to a chain-like cylinder fracture system at $b << a\sqrt{D/d}$ (with $t_2 = (D/d)^2 t_1$)

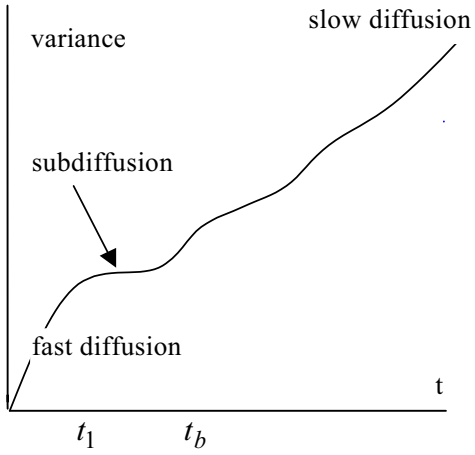

Figure 3. Scheme of dispersion-time dependence for an infinite sequence of flat fractures at $b << a(D/d)$ (with asymptotic behaviour $\sim(a/b)Dt$) and for a set of cylindrical parallel fractures, uniformly distributed in space, at $b << a\sqrt{D/d}$ (with asymptotic behaviour $\sim(a/b)^2 Dt$)

Qualification and validity of a smeared fractures modelling approach for transfers in fractured media

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A b s t r a c t : We propose here a Smeared Fractures approach dedicated to Mixed and Hybrid Finite Element scheme. This numerical scheme is adapted for such highly heterogeneous media and in particular guaranties exact conservation of mass flow for each mesh leading to mass conservative transport results. We developed a method to estimate associated flow and transport parameters. Having implemented the developed smeared fracture approach in our CAST3M code, we evaluate the precision of the results for various mesh sizes and for different flow and transport regimes, ranging here from dominant advective transport in the fracture network to dominant diffusion transport controlled by the matrix blocks. This is achieved by comparing the smeared fracture approach simulations to reference calculations obtained by explicitly meshing the fractured system. We presently consider 2D systems with permanent flow, Eulerian transport in the whole system.

PRESENTATION

The basic idea of the approach is not to mesh the fracture network but to take the presence of fractures into account by means of continuous heterogeneous fields (permeability, porosity, head, velocity, concentration...). This line, followed by different authors (refer to Svensson 2001, and Tanaka *et al.* 1996), is referred as Smeared Fracture approach and presents the following advantage: no dedicated spatial discretization effort is required (we use a basic regular mesh, simulations can be done on a rough mesh saving computer time). This makes this kind of approach very promising for taking heterogeneity of properties as well as uncertainties into account within a Monte Carlo framework for instance. Furthermore, the geometry of the matrix blocks where transfers proceed by diffusion is fully taken into account contrary to classical simplified 1D approaches for instance. Nevertheless continuous heterogeneous field representation of a fracture medium requires a homogenisation process at the scale of the mesh considered and constant mesh size might not be appropriate to simulate contrasted regimes.

Initially, we have to identify meshes corresponding to a fracture, the number of X type cells N_X and Y type cells N_Y (fig.1) and after provide the adapted parameter values (transmissivity, porosity, dispersivity...) to the mesh.

- The equivalence of the flux through the reference fracture and the equivalent conductor is easy to write based on the numerical scheme considered. For Mixed and Hybrid Finite Element, conservation of the quantities is guaranteed for each mesh by the introduction of four unknowns (traces affected to the centre of the element edges in addition to the classical unknowns corresponding to the centre of the elements). These allow for jointed estimation of the fluxes (gradients) as well as the values of the unknowns within the mesh (see Dabbene 1998). So we can determine a relation between T_{sf} and T_{ref} :
- $$T_{sf} = \frac{(3N_X + 2N_Y).e}{3L} T_{ref}$$
  where e and L are respectively the aperture and the length of the fracture (sf = smeared fracture and ref = explicit modelling).
- The equivalent dispersion tensor is here derived as a scalar value based on the same considerations as for the equivalent transmissivity.
- Equivalent porosity is estimated as for Lagrangien approach: transition times can be calculated for both type of elements encountered on the smeared fracture geometry and we obtain:

$$\omega_{sf} = \frac{L.e}{(N_X + N_Y)\Delta X^2}$$

For a fracture network, the same procedure is applied for each conductor, the value affected to the intersection is the maximum of all met in this mesh. The type of transfer at the fracture intersections is full mixing.

The Smeared Fracture approach was previously tested on different fracture networks for permanent flow simulations and has given good results. Preliminary results involving Eulerian transport limited to the fractured network were promising.

RESULTS

The smeared fracture approach for Eulerian transport is here evaluated for problems involving matrix diffusion for different flow regimes. The retention effect associated with matrix zones indeed depends upon the contact time with the plume. For quick flow conditions (typically forced flow conditions), advection in the fracture network is dominant and retention effects associated with matrix diffusion are limited. For slower regimes (typically post closure conditions for nuclear waste disposal issues), matrix diffusion plays a major role resulting in a globally diffusion dominant regime. We evaluate here the smeared fracture approach for different flow regimes as well as discretization strategies. We consider for sake of illustration a simple system involving a single fracture within a porous block (tilted 30°) and three regimes :

- A dominant advective regime (K1).
- An intermediate regime (K2).
- A dominant diffusive regime (K3).

We show on fig.2 the breakthrough curves for a Dirac injection in the system. The influence of the flow regimes shows up classically in delays in arrival times as well as decrease of the peak level (fig.2). We plot on figs 3 to 5 the total flux exiting the system for the three regimes considered and for different levels of discretization. The curve with large circle corresponds to the reference calculation obtained by meshing explicitly the fracture and the block. Globally, the Smeared Fracture approach (i) works better for diffusive dominant regimes than for advective dominant (this result is not surprising because matrix blocks in the Smeared Fracture approach are potentially underdiscretized for dominant advective regimes); (ii) provides better results when refining the mesh. The same trends are observed for other quantities like evolution of total mass in the fracture or matrix subsystems (not illustrated here).

More detailed comments follow :

- Case K1: (dominant advective regime fig.3) : peak arrival time is well met with errors of the order of 5% but the peak level can be missed by 50% for coarse discretizations.
- Case K2: (intermediate regime. fig.4) : the level of the peaks as well as their arrival times are better.
- Case K3 (diffusive regime. fig.5) : results show overall good qualitative as well as quantitative results. Whatever discretization, we obtain good peak arrival time and peak maximum differs by less than 10%.

To conclude, precision is maximal for diffusion dominant regimes. It is acceptable for the intermediate regime within a precision range of 10%. For the dominant advective regime we have to use a refined discretization to model transfers with equivalent quality.

CONCLUSIONS AND PERSPECTIVES

This approach presents good results in terms of precision, low computer coast and stability of numerical scheme. The quality of the results more closely depends on fracture regimes as well as space discretization. The Smeared Fractures approach is more specially dedicated for long transport time where the actual geometry of the matrix blocks have to be taken into account.

REFERENCES

Dabbene F (1998) Mixed Hybrid Finite Elements for transport of pollutants by undergound water. Proc. 10th conference on finite elements in fluids, Tucson, Arizon

Svensson U (2001) A continuum representation of fracture networks. Part I: Method and basic test cases. Journal of Hydrology 250:170-186

Tanaka Y, Minyakawa K, Igarashi T, Shigeno Y (1996) Application of 3D smeared fracture model to the hydraulic impact of the Aspo tunnel. SKB Report. ICR 96-07

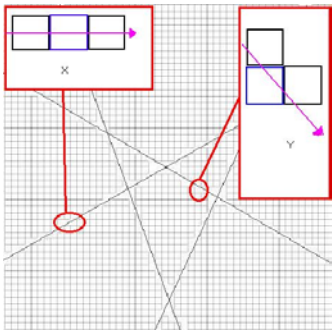

Figure 1. Smeared Fractures mesh with X and Y type cells

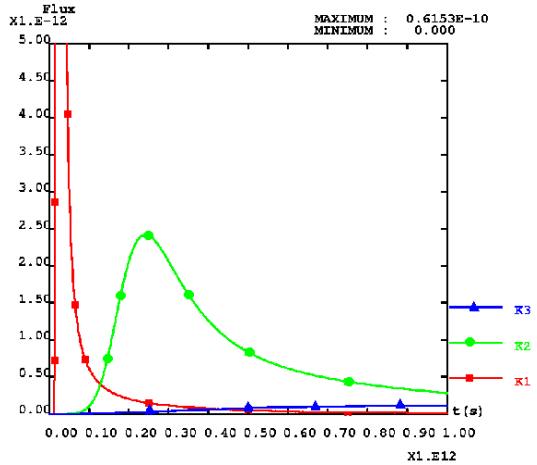

Figure 2. Three different transport regimes (Breakthrough curves)

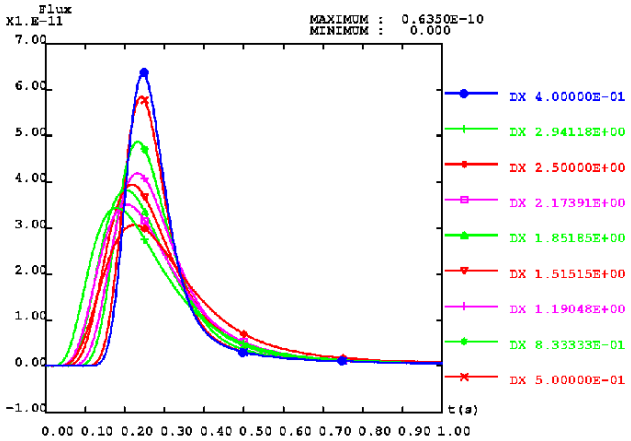

Figure 3. Total fluxes at the outlets for regime K1

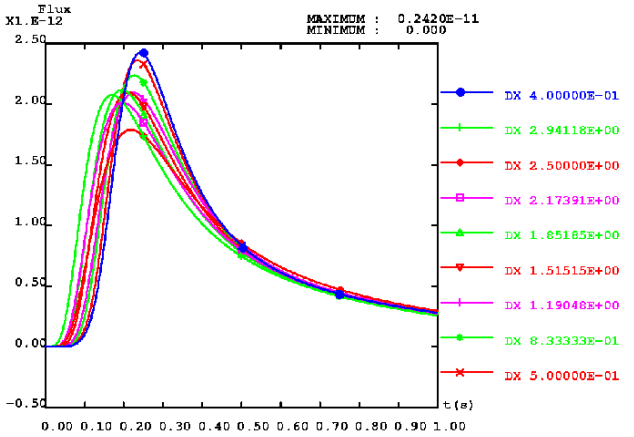

Figure 4. Total fluxes at the outlets for regime K2

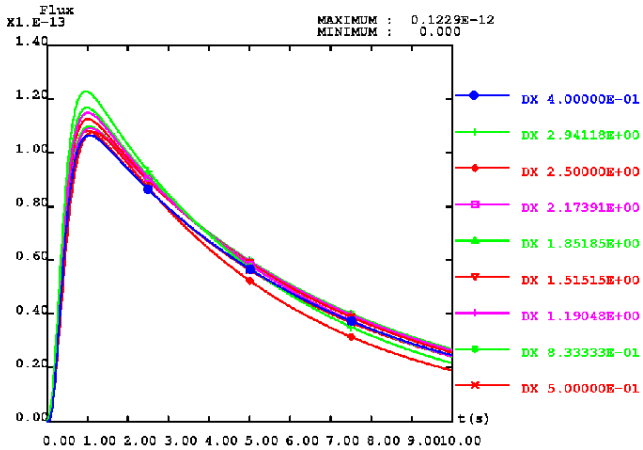

Figure 5. Total fluxes at the outlets for regime K3

A study of the dispersion in a single thin fracture using Positron Emission Projected Imaging

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A b s t r a c t : Transport in a natural fracture is studied using Positron Emission Projection Imaging. This non-invasive technique allows measuring the activity of a radioactive solution giving two-dimensional maps of the concentration of a conservative tracer injected at constant flow rate in the plane of the fracture. The technique is also used to obtain the aperture distribution. Transport process is analysed in term of geometrical dispersion controlled by the heterogeneity of the flow velocity field. Three modelling approaches are compared: i) the flow is approximated by the Reynolds equation (2D approach) , ii) 3D Stokes equation is solved and macro-dispersion emerges from the local molecular diffusion and flow field heterogeneities solely and iii) 3D Navier-Stokes density driven flow is implemented in order to explain the anomalous pattern of dispersion observed.

INTRODUCTION

Recent improvements for assessing transport in fractures have focussed on the emergence of new modelling concepts for non-stationary and/or scale-dependent dispersion regime in relation with the fracture geometry and velocity field heterogeneities (Detwiler *et al*. 2000; Plouraboué *et al.* 1998). The dispersion coefficient can be written as a sum of the geometric dispersion coefficient and Taylor dispersion coefficient; if the correlation length of the velocity field is small compared to the system size, then Taylor dispersion dominates, otherwise, channelling dominates with a strong control of the larger aperture zones (Johns and Roberts 1991).

Beside, laboratory observations on natural samples become tractable thanks to the development of powerful tomographic methods. Although restricted to small extension domains, experiments are essential for testing and validating theoretical models and numerical simulations. We discuss here the results of a tracer experiment for which Positron Emission Projection Imaging (PEPI) technique is used to determine the spatio-temporal distribution of a tracer migrating in a natural fracture.

EXPERIMENTAL SETUP AND DATA ACQUISITION

PEPI is based on the recording of synchronous opposed-collinear gamma rays resulting from the annihilation reaction between the positron emitted by the radio-isotopes and the surrounding electrons (Gresswell *et al.* 1998). The isotope concentration is directly proportional to the number of emitted photon so that this non-invasive technique allows measuring the spatial distribution of the radioisotope- enriched tracer within the fracture.

The tracer is prepared by irradiation of metallic copper, producing a controlled enrichment in the radioactive isotopes ^{64}Cu, then, dissolved in nitric acid and complexed by Copperethylenediaminetetraacetic acid. The solution is adjusted at a neutral pH using sodium hydroxide in order to minimise fluid-rock interactions and diluted in pure water to obtain the optimal radioactivity level for the PEPI camera. The same procedure, but with non-irradiated copper, is followed to prepare the passive fluid used to saturate the sample. The first stage consists in calculating the fracture aperture $a(x,y)$ from the spatial distribution of the ^{64}Cu activity $A_a(x,y)$ measured when the fracture is completely filled with the tracer. After a complete flushing, the tracing experiment consists in injecting the tracer at a constant flow rate in the plane of the fracture. The tracer activity distribution is integrated over 10 minutes which ensure a mean displacement smaller than 2 pixels (U < 1 mm/minute). The aperture-averaged concentration $C(x,y,t)$ is equal to the ratio of $A_t(x,y,t)$, the activity of thetracer, to $A_a(x,y)$ (Fig.1). At the end of the experiment the fracture topography is measured by injecting a dyed resin into the fracture, then sawing the block into 1 cm slices.

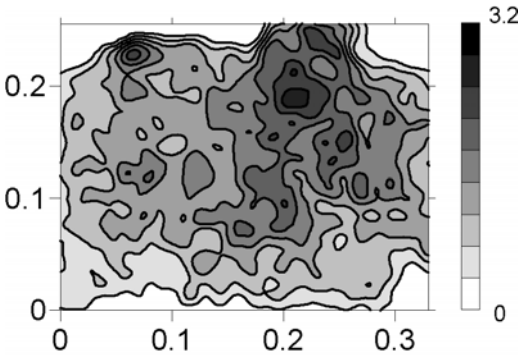

Figure 1. Aperture field in mm

RESULTS ANALYSIS

The first question, arising when studying hydrodispersive transport, is whether the process is Fickian, and to identify the respective role of the advection and diffusion transport characterized by the aperture-scale Peclet number, $Pe = aU/d_m$, where U is the aperture-averaged fluid velocity and d_m the diffusion coefficient. Here, the average $\langle Pe \rangle_{xy}$ is close to 70 which suggest that the longitudinal effect of diffusion is of little importance compared to advection. The velocity fluctuations (Fig.2) are here more than 5 times the average velocity. Following criteria proposed by Plouraboué *et al.* (1998), geometrical dispersion regime is dominant.

For short extension samples, the mixing zone change can be studied by analyzing the concentration profiles $C(x,t)$. For the case of a tracer injected at constant rate between parallel plates, the pure-advection concentration profile is $C(x,t)=(1-2x/3Ut)^{1/2}$. However, in our experiment, the concentration profiles fit better the relation $C(x,t)= \exp(-x/Ut)$ showing that the mixing zone increases with t instead of $t^{1/2}$ as prescribed by the dispersion model. This scaling is again a characteristic of the geometrical regime of dispersion.

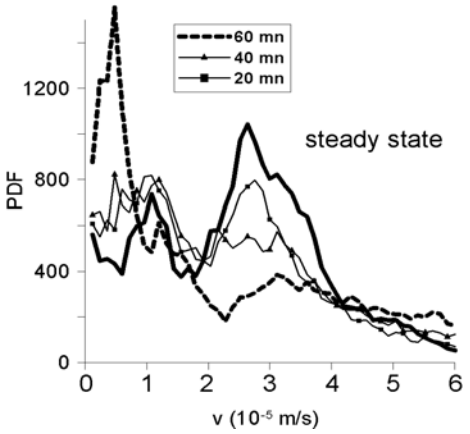

Figure 2. Probability Density Function of the velocity $|U(x,y)|$ for isodensity (steady state) NS simulation and density dependent flow at 20, 40 and 60 mn showing a strong modification of the flow field distribution

DISCUSSION

Transport is studied through 2D and 3D numerical simulations (Fig.3). In the first case, fluid velocity is assumed to be governed by Reynolds equation $U = -(a^2/12\mu)\nabla P$ (with P the pressure supposed constant over the aperture and μ the dynamic viscosity). For incompressible fluid the continuity equation is $\nabla.(a\ U) = 0$. Transport is governed by the classical ADE $a\partial C/\partial t+\nabla.(a\ U\ C) - \nabla.(a\ D\ \nabla C) = 0$ where $D = 1 + Pe^2 / 210$ (Taylor's formula).

Iso-density 3D simulations are based on the resolution of Navier-Stokes (NS) equation without body forces: $\nabla p=\mu\nabla^2 u-\rho(u.\nabla u)u$ with $\nabla.u = 0$ and $u = 0$ on the fracture walls. The transport equation reduces here to $\partial c/\partial t + u\nabla c - d_m\nabla^2 c = 0$. The z-averaged concentration fields, $C(x,y,t)=1/a(\int c dz)$, can be directly compared with the PEPI data.

Results from 2D and iso-density 3D show very similar patterns emphasizing that: (1) the velocity distributions across the fracture sections stay parabolic, independently of the topographic and aperture changes ($u(z) \cong u_0(1 - 4z^2/a^2)$ where u_0, is the maximum velocity), the changes in $\partial p/\partial x$, $\partial p/\partial y$ introduced by the aperture change are negligible, and (2) the introduction of a local-scale Taylor dispersion approximation is valid in this case.

However, the comparison of the data with the former models displays strong discrepancies that we attribute to gravity effects due to weak unanticipated density differences between the tracer solution and the saturating solution. We reiterate the former simulation using transient form of the NS equation $\nabla p=\mu\nabla^2 u-\rho\ (u.\ \nabla u)u+\rho(g-\partial u/\partial t)$, where g is the gravity vector, and the continuity equation $\partial\rho/\partial t=-\nabla.(\rho\ u)$. A density difference of $5\ 10^{-4}$ is assumed. This example emphasizes the strong control of the topography compared to the aperture effects; the fluid does not follow the high aperture path anymore.

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REFERENCES

Detwiler RL, Rajaram H, Glass RJ (2000) Solute transport in variable-aperture fractures: An investigation of the relative importance of Taylor dispersion and macrodispersion. Water Resour Res 36(7):1611-1625

Greswell R, Tellam JH, Lloyd JW, Parker DJ (1998) Positron Emission Projection Imaging studies of solute movement through rocks. Int Asso Hydro Ann Meet 28:561-566.

Johns RA, Roberts PV (1991) A solute transport model for channelized flow in a fracture. Water Resour Res 27(8):1797-1808

Plouraboué F, Hulin JP, Roux S, Koplik J (1998) Numerical study of geometrical dispersion in self-affine rough fractures. Phys Rev E 58(3):3334-3346

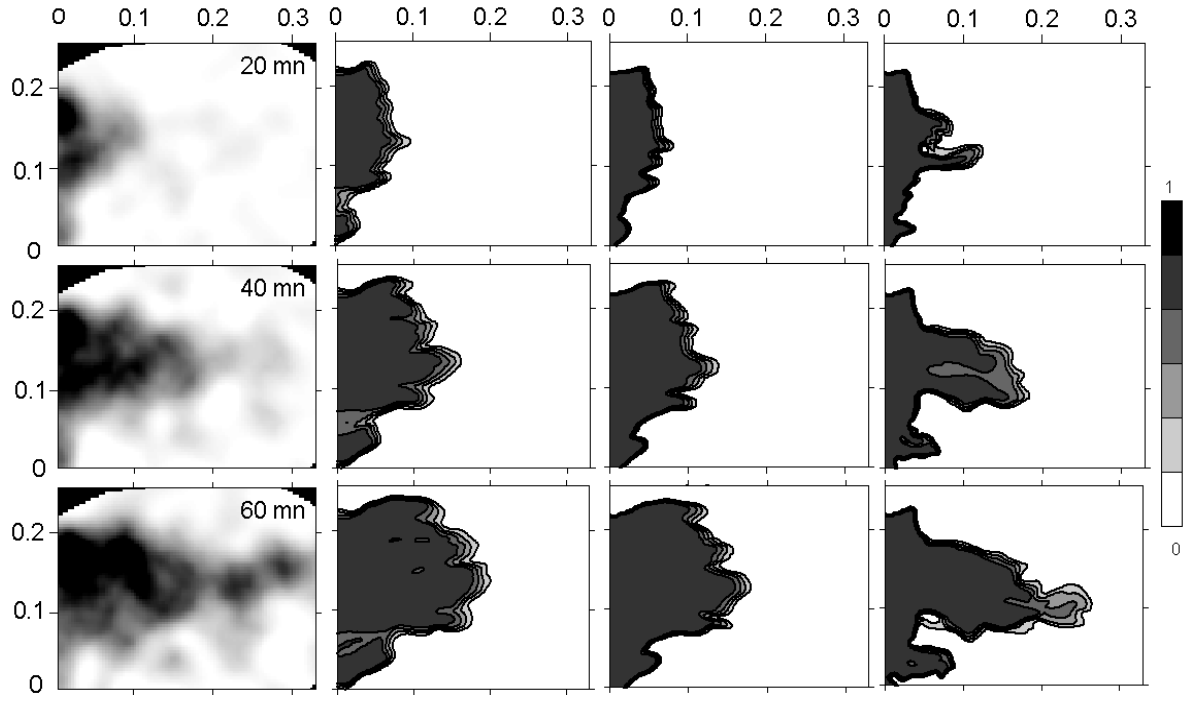

Figure 3. First column: PEPI concentration (65 x 51 pixels of 4.8 mm2), second column: Reynolds/Taylor computed concentration, third column: isodensity NS computed concentration, and last column: density driven dispersion (transient NS). Tracer is injected from the left side of the fracture

A statistical approach to build up a multi-continuum model describing flow and transport processes in fractured permeable sandstone

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A b s t r a c t : This paper presents a multi-continuum approach to simulate flow and transport in fractured porous media. A simplified 2D model aquifer is chosen to demonstrate the applicability of the multi-continuum model. Calibration is done with respect to measured tracer breakthrough curves which can be associated with different clusters representing varying rock properties. Determined parameters allow a good description of the system behaviour at the modelling scale (2.5 x 2.5 m²).

OBJECTIVE

The objective of the proposed paper is to present the ongoing modeling using the multi-continuum approach and future development of investigations concerning flow and transport in fractured permeable formations in the framework of the Aquifer Analogue Project. The research of the Aachen project group (PG4) during the third phase (2001 - 2003) of this project is focused on investigations concerning the possibilities and limits of the multi-continuum model. Furthermore, the sensitivity of coupling and transport is going to be analyzed.

APPROACH

Although numerical models are available, there is a gap between the capability of the models on the one hand and the limitations concerning geohydraulic and geophysical investigation techniques for fractured formations on the other hand. To overcome this difficulty field, laboratory and alternative numerical experiments are performed within the Aquifer Analogue Project for different length scales. Based on this high density information from the physical experiments multi-continuum models are evaluated with regard to saturated flow and transport phenomena. The goal of the investigation of the PG4 is to work out equivalent parameters for the fractures and the matrix and to specify the exchange parameters, which can be seen as calibration parameters. Using these models different concepts are analyzed, which allow to transfer equivalent parameters from one scale to a larger one. The PG4 has developed a multi-continuum model (STRAFE), which allows for modeling saturated and unsaturated groundwater flow as well as transport processes in a fractured aquifer.

As the equivalent parameters are difficult to be determined, the idea is to characterize the experimental results by means of statistical evaluations. For this a cylindrical core (see fig.1) is taken from the field and migration experiments are performed in the laboratory on a small scale. The measured breakthrough curves are characterized by statistical values. A multi-continuum model is built up by calibrating the hydraulic components and the exchange terms to these statistical characteristics. The multi-continuum model is then used to describe the entity of the measurements by a coupled system. The aim is to transfer the multi-continuum model of the core to a larger scale.

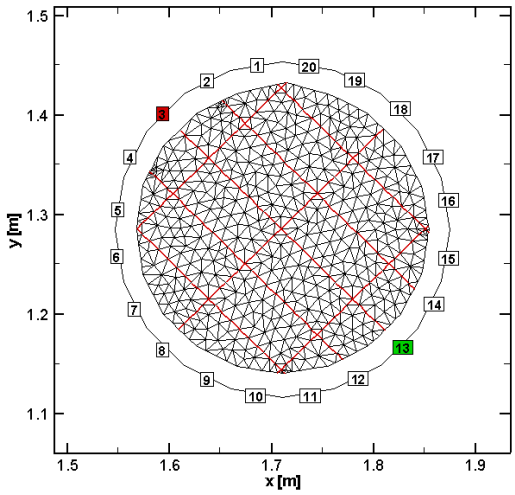

Figure 1. Cylindrical core: finite element mesh and port location

RESULTS

To examine this approach a simplified two-dimensional model aquifer (2.5 x 2.5 m²) is chosen to perform discrete modelling. A cylindrical core (0.3 m) is extracted to perform discrete (port-to-port) measurements on a small scale. The resulting breakthrough curves are interpreted by a cluster analysis (see fig.2). A multi-continuum model is calibrated to these clusters. The parameters that are determined allow a good description of the system behaviour on this scale.

This model is then compared to the discrete results of the simulated breakthrough curves of the model aquifer on a larger scale (2.5 m). Furthermore a multi-continuum model based on the geometric characteristics is built up and compared to the other models.

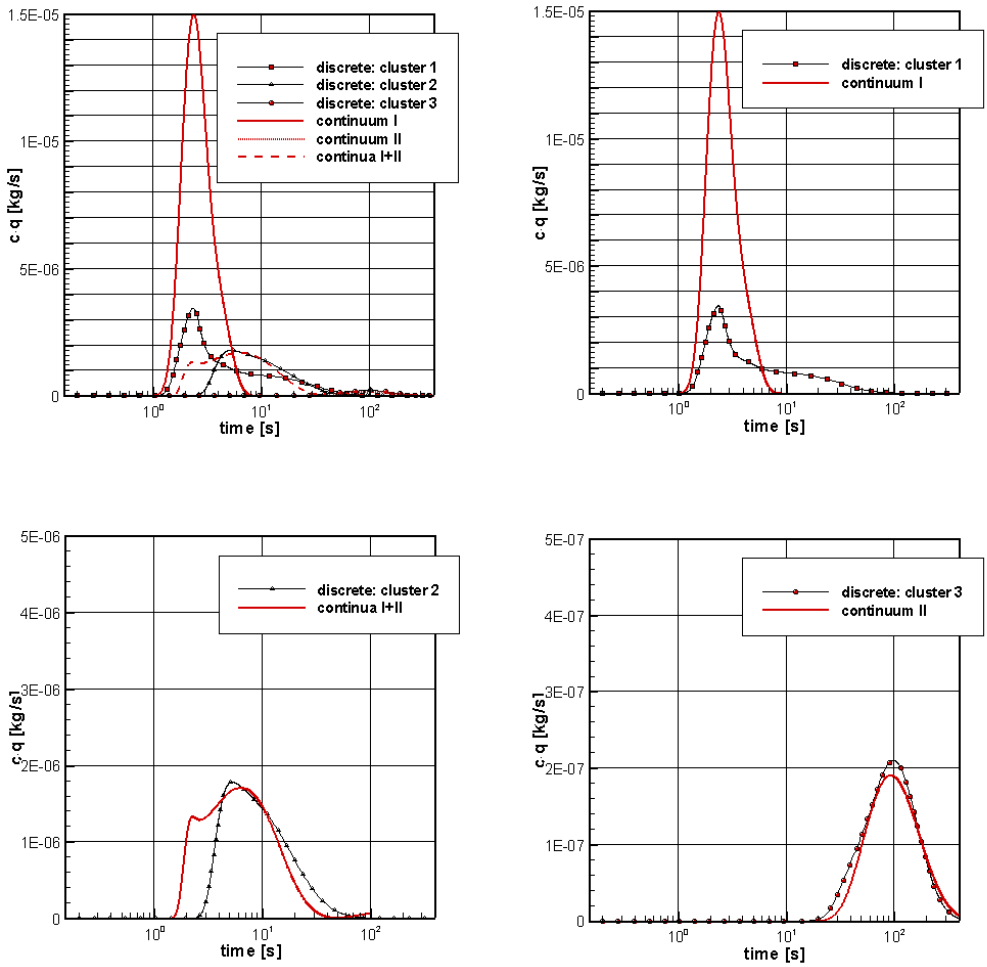

Figure 2. Square mean root breakthrough curves for all clusters in detail; discrete versus multi-continuum results

Tracer breakthrough, hydraulic properties and fracture networks at sub-continuum scales in aquifers

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A b s t r a c t : Fractures spaced ~0.1 to ~10 m impart continuum scales to fractured aquifers which may exceed the size of many practical problems. Sub-continuum flow models often use statistical simulations of explicit fracture networks, which can lead to serious problems of system identification and uniqueness. To address this problem the aim of the research is to determine whether tracer breakthrough curves may be used to characterise fracture topology at sub-continuum scales and to answer the question do there exist topological classes of fracture networks that produce breakthrough curves of an identifiable and distinctive type? Results so far indicate that 2-D fractured porous media can produce a large variety of tracer breakthrough curves, including two patterns rather commonly seen in field data the backward tailed unimodal, non-Fickian type and the Fickian.

METHODOLOGY

Our approach is one of forward modelling, starting with a prescribed fracture network in a homogeneous permeable medium. The flow field and tracer transport are simulated for each network in turn using a 2-D finite difference numerical code (Odling and Webman 1991; Odling and Roden 1997). Linear and radial flow fields can be simulated, allowing the results to be compared with natural and forced gradient tracer tests conducted in field experiments. So far only linear flows have been studied. The output from the model - the tracer breakthrough curve - is a record of the fracture geometry, flow field and bulk equivalent permeability of the model and of the chosen injection pattern.

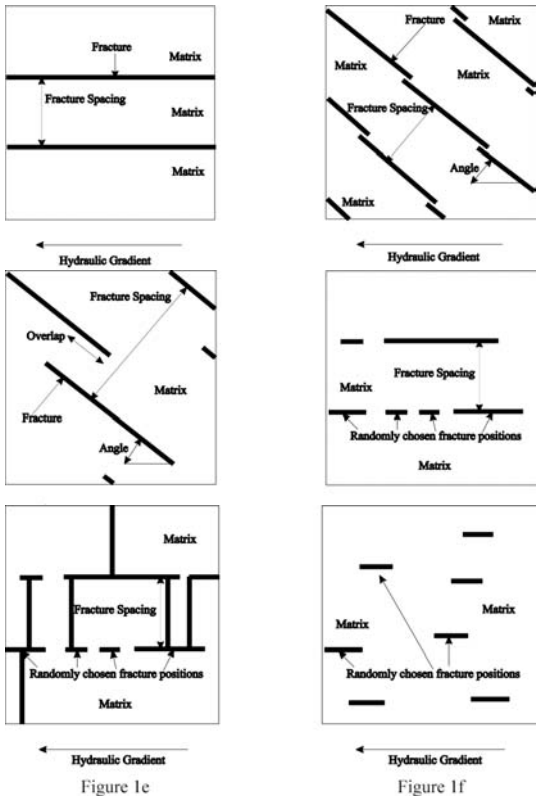

Figure 1. (a to f). Fracture patterns modelled

By repeating the modelling procedure for different networks, we aim to explore the combinations of bulk permeability and breakthrough curves which each can produce. Our hope is that by combining measured breakthrough curves from field experiments with these simulations we shall be able to constrain the interpretation of fracture network topology that exists within a rock mass of interest. In this way it is hoped that the problem of non-uniqueness in fracture rock characterisation may be partially overcome. Fig.1 gives examples of the type of fracture patterns that have been modelled: a continuous pattern (Fig.1a); an en echelon pattern with small overlap (Fig.1b); an en echelon pattern with large overlap (Fig.1c); a discontinuous pattern (Fig.1d); a 2-set ladder type pattern (Fig.1e); and a completely random pattern (Fig.1f). Both uniform and random fracture spacing have been modelled.

Figs 1a and 1d might represent either bedding planes or vertical joints depending on whether the plane of the 2-D model is considered as being vertical (fractures are bedding planes) or horizontal (fractures are joints). Figs 1b, 1c and 1f have greatest similarity to single sets of vertical joints so that the 2-D model plane may be considered as horizontal for these two patterns. Fig.1e might represent either bedding planes and vertical joints or 2-sets of vertical joints (Gross 1993; Bai *et al*. 2002). The fracture spacing, angle to hydraulic gradient, aperture and degree of connectivity have been systematically altered for each pattern. The effects of percolation for the 2-set case are also being investigated.

RESULTS

Results so far indicate that 2-D fractured porous media can produce a large variety of tracer breakthrough curves, including two patterns rather commonly seen in field data: the backward tailed unimodal, non-Fickian type (Ptak and Teutsch 1994; Barnes 1999; Becker and Shapiro 2000; Meigs and Beauheim 2001) and the Fickian. While field types may arise from other processes, such as double-porosity diffusion, our study shows that under certain conditions they may also be produced as a result of simple inhomogeneities with coarse scale relative to the region of interest, in agreement with recent studies of transport through fractured porous media. For the 1-set case, it is the combination of the spacing, aperture and angle to the direction of the hydraulic gradient which dictates the type of curve produced and not necessarily the type of fracture pattern.

Approximately two thousand patterns have been simulated. The great majority of breakthrough curves fall into one of five distinct classes, examples are shown in Fig.2, although transitional cases between the classes can also be recognised. 1-set patterns produce the full range of curve types but results so far show that 2-set patterns produce a restricted range of curve types, the majority falling into the Type 2 and Type 3 categories.

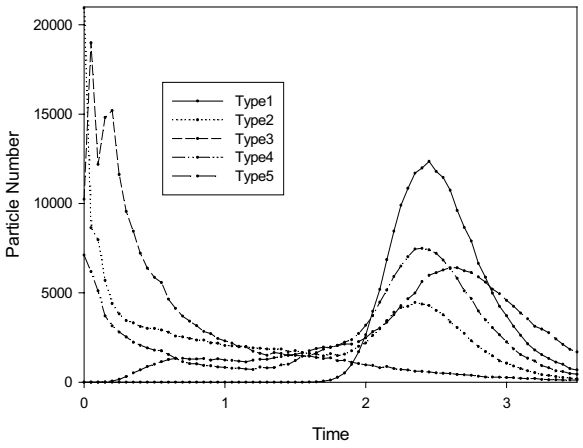

Figure 2. Examples of five distinct classes of breakthrough curves produced by modelling exercise. (Type 1: matrix-like; Type 2: L-shaped curve with very early breakthrough and peak and backward tailing; Type 3: L-shaped curve with very early breakthrough but with a rise to the peak and backward tailing; Type 4: bimodal curve with early breakthrough and peak plus a matrix-like peak at later time; and Type 5: forward tailed matrix-like peak)

We have examined and classified the variety of breakthrough curves that are produced by simple, 1-set, class of fracture networks and we are in the process of examining the breakthrough curves produced by more complex 2-set patterns. The breakthrough curves are classified using Principal Component Analysis (PCA). The first two principal components account for the majority of the variance in breakthrough curve shape such that curves of the same type lie in similar regions of the component space. Each curve has an associated fracture spacing, aperture, angle of rotation to the hydraulic gradient, permeability and pattern. We intend to explore the predictive capability of PCA. Given a breakthrough curve, produced by a previously un-modelled pattern, we hope to show that, using PCA, it is possible to predict (or at least reduce the number of possibilities of) the fracture spacing, aperture, angle of rotation to the hydraulic gradient and pattern responsible for producing that curve. Fig.3 shows how five hundred of the modelled breakthrough curves orientate themselves in the principal component space.

The curves in the upper-left hand corner are typical of Type 2 and Type 3 and the curves in the upper-right hand corner are typical of Type 1. There is a gradual change, as you move from the right side to the left side of Fig.3 from Type 1 curves through Type 4 and 5 curves to Type 2 and 3 curves. If the third principal component dimension is included the separation of the curves becomes even more apparent. The method requires that the data set is large enough in order that the covariance matrix of the breakthrough curve data is not altered when the positions of additional breakthrough curves, not previously modelled, are determined in the principal component space. To ensure that the covariance matrix is not altered as many patterns as possible will be modelled.

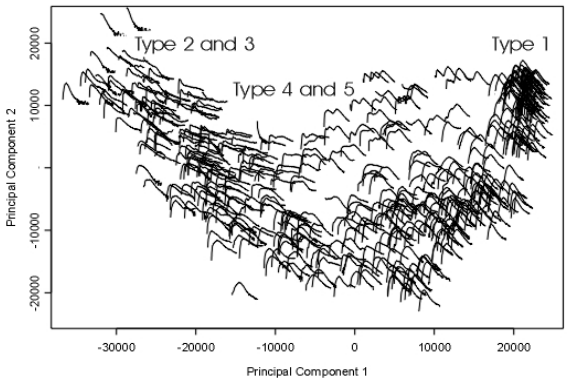

Figure 3. Breakthrough curve position in principal component space

CONCLUSIONS

From around two thousand simulated breakthrough curves, a classification scheme has been devised and linked to fracture pattern properties. The great majority of breakthrough curves fall into one of five distinct classes, including two patterns rather commonly seen in field data the backward-tailed unimodal, non-Fickian type and the Fickian type. For the 1-set case, it is the combination of the spacing, aperture and angle to the direction of the hydraulic gradient which dictates the type of curve produced and not necessarily the type of fracture pattern. Results so far show that 2-set patterns produce a more restricted range of curve types, the majority falling into the Type 2 and Type 3 categories.

PCA may prove to be a useful tool in the classification of breakthrough curves. More importantly given a breakthrough curve and a permeability PCA may be able to be used to predict the fracture aperture, spacing, angle to hydraulic gradient and fracture pattern responsible for producing that curve.

REFERENCES

Bai T, Maerten L, Gross M, Aydin A (2002) Orthogonal cross joints: do they imply a regional stress rotation? J of Struct Geol 24:77-88

Barnes S (1999) Karstic groundwater flow characteristics in the Cretaceous Chalk aquifer, Northern Ireland. Quart J of Eng Geol 32:55-68

Becker MW, Shapiro AM (2000) Tracer transport in fractured crystalline rock: Evidence of nondiffusive breakthrough tailing. Water Res Res 36(7):1677-1686

Gross M (1993) The origin and spacing of cross joints: examples from the Monterry Formation, Santa Barbara Coastline, California. J of Struct Geol 15(6):737-751

Kosakowski G, Berkowitz B, Scher H (2001) Analysis of field observations of tracer transport in a fractured till. J of Cont Hydrol 47:29-51

Meigs LC, Beauheim RL (2001) Tracer tests in a fractured dolomite 1. Experimental design and observed tracer recoveries. Water Res Res 37(5):1113-1128

Odling NE, Webman I (1991) A 'conductance' mesh approach to the permeability of natural and simulated fracture patterns. Water Res Res 27:2633-2643

Odling NE, Roden J (1997) Contaminant transport in fractured rocks with significant matrix permeability, using natural fracture geometries. J of Cont Hydrol 27:263-283

Ptak T, Teutsch G (2001) Forced and natural gradient tests in a highly heterogeneous porous aquifer: instrumentation and measurements. J of Hydrol 159:79-104

Modelling advective and diffusive transport in fractured chalk

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A b s t r a c t : In the Chalk aquifer of NE England, diffusion of contaminants from fractures into the low permeability but high porosity matrix is of concern. Application of two modelling approaches are presented. A discrete fracture flow and transport model is applied to a series of en echelon fractures under natural groundwater flow rates, and a dual porosity model is applied to pressure conditions during a tracer test. The discrete fracture model shows that at natural flow rates, the presence of diffusion can significantly enhance contaminant transport, even when fracture apertures are small (120 μm). The dual porosity model suggests that fracture porosity is around 0.1-0.2%. This corresponds to wide apertures of the order of 1-2 mm for fractures spaced at 1m, to 100-200 □m at fracture spacing of 10 cm. This suggests that very highly fractured or brecciated horizones are dominating the flow.

FLOW AND CONTAMINANT TRANSPORT IN FRACTURED CHALK

In the Cretaceous Chalk aquifer of north-eastern England, the bulk permeability of the aquifer is provided by fractures and faults while marl (clay rich) bands provide potential vertical flow barriers. This enhances flow in the direction of bedding, although recent tracer experiments (Hartmann, West and Odling, this volume) show that some cross-bedding flow does occur, probably along vertically persistent joints and faults. It has long been appreciated that the high porosity coupled with low permeability of the chalk rock matrix enhances the impact of solute diffusion into the rock matrix from fractures (Grisak and Pickens 1980, Barker and Foster 1981). Most existing models of this process concentrate on transport and diffusion on the scale of one fracture and matrix block, and ignore advection in the matrix. In this presentation, a model of advective and diffusive transport in which many fractures can be included is presented. This model and a dual porosity model which takes matrix diffusion into account (Moench 1995) are used together with results from the recent tracer test in the Chalk aquifer of north-eastern England (Hartmann *et al.,* West *et al*., this volume) to investigate the importance of matrix diffusion and advection in solute transport within the chalk.

MODELLING METHODS

a) Discrete fracture flow and transport model

The modelling method combines the flow field from a 2D finite difference discrete fracture flow model (fig.1) with a particle tracking method for modelling diffusive and advective transport. In the 2D finite difference flow model, both matrix and fractures are discretized, allowing the detailed geometry of the fracture network to be represented. Care is taken to maintain the connectivity of the fracture network on discretization. Solute transport is modelled using a particle tracking technique where the times taken for particles to travel discrete distances are recorded. Diffusion parallel (with or against) or perpendicular to the advection velocity given by the flow field is allowed. Within a fracture, the parabolic velocity profile is incorporated.

The model was compared to two previous models in the literature by Grisak and Pickens (1980) and Barker and Foster (1981) which employ analytical solutions for solute transport. A comparison of results shows that they are very similar but that the present model predicts slightly less transport of contaminant from the fracture into the matrix.

b) Dual porosity modelling

An advection-dispersion-matrix diffusion code for radially convergent conditions ('pipe and sponge' model), supplied by the USGS (Moench, 1995), was applied to the tracer test breakthrough curves. Input parameters include the effective diffusion coefficient, block size (fracture spacing), fracture porosity and aquifer thickness. This modelling can provide an indication of the spacing of hydraulically active fractures, and of the importance of fracture coatings in inhibiting diffusion of solutes between the matrix and the fractures.

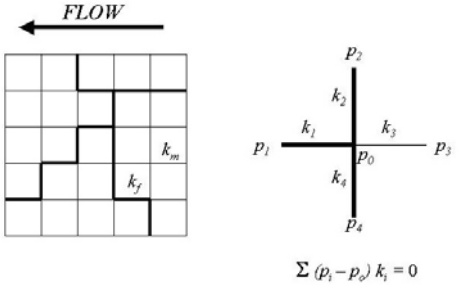

Figure 1. The 2D finite difference flow model. Fractures and matrix are discretized on a regular grid

MODELLING RESULTS

a) Discrete fracture flow and transport model

The model is applied to a pattern of en echelon fractures (joints), a common ocuring geometry, in a 1 m square block. Matrix properties typical of Chalk in NE England are used; permeability 10^{-9} m/s, porosity 20%, and a diffusion coefficient of 10^{-10} m^2/s. The pressure gradient is set to 10 Pa/m which is representative of the natural gradient in the area of the tracer test. A fracture aperture of 120 μm is assumed. The resulting pattern of contaminant after 100 days, fig.2, shows that there is significant contaminant in the matrix, particularly in the overlap sections between fracture segments. By comparison, when matrix diffusion was not included, contaminant had not passed the first fracture segment in the same time. The breakthough curves for models with, and without diffusion are shown in fig.3. When diffusion is included breakthrough occurs in a little over 4 months but takes over 200 years when it is not. Thus, while in connected fracture systems, matrix diffusion reduces solute transport, for unconnected fracture systems and low advection rates representative of natural hydraulic gradients, diffusion can act to significantly enhance solute transport through the rock.

b) Dual porosity modelling

A series of simulations were carried out using the advection-dispersion-matrix diffusion code prior to conducting the tracer test with the aim of identifying appropriate test conditions. Simulations were carried out for two scenarios:

- flow via 50m thickness of Chalk, $\phi_f = 0.01\%$ (runs 1-4)
- flow restricted to 10m total thickness, $\phi_f = 1.8\%$.(runs 4-8)

Selection of flowing thicknesses and fracture porosities was based on geophysical logging from the tracer site and previous tracer tests conducted on Chalk (Atkinson *et al.* 2000; Garnier *et al.* 1985). Block radii of 0.3m, 1m, 3m, were based on fracture spacings observed in quarry exposures and core from the tracer

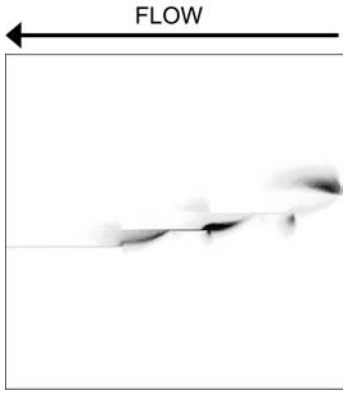

Figure 2. Contaminant distribution after 100 days from flow due to a pressure gradient of 10 Pa/m in a region 1x1 m containing a series of en echelon, unconnected fractures

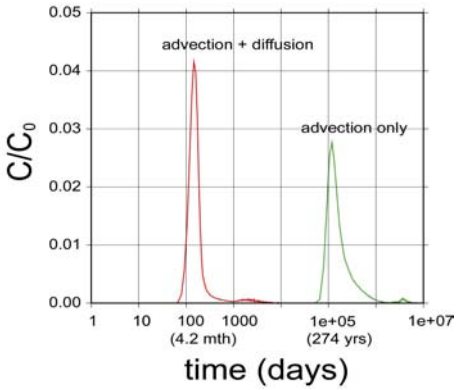

Figure 3. Breakthrough curves for contaminant concentration at the outflow end of the series of en echelon fractures in fig.2

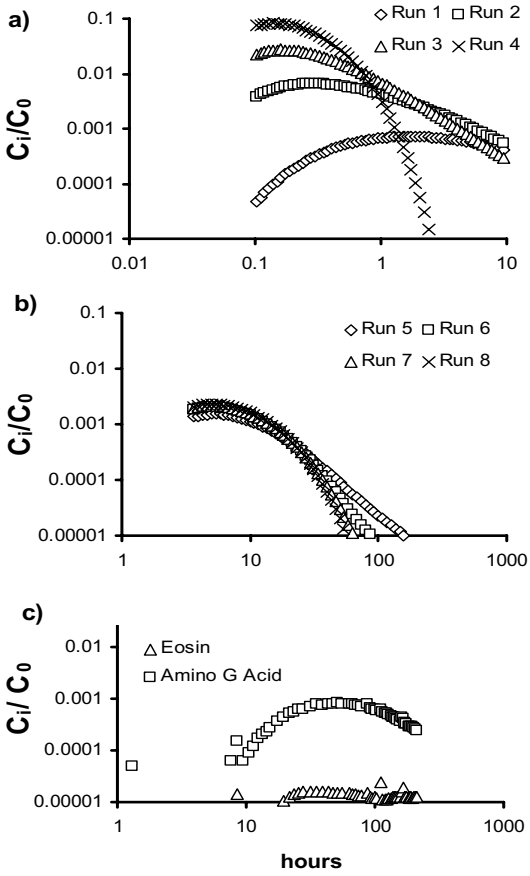

Figure 4. Dual porosity modelling results for a) ϕ_f = 0.01% b) ϕ_f = 1.8% , and c) tracer test breakthrough curves

test site. A block size of ∞ was also tested as the limiting case of negligible interchange of solute between fractures and matrix. The matrix diffusion co-efficient of 10^{-10} m^2/s and matrix porosity of 23% are based on laboratory tests. A pumping rate of $690m^3$/day was assumed. The run parameters are:

RUNS	Flowing Section (m)	ϕ_f%	Block radius (m)
1-4	50	0.01	0.3, 1, 3, ∞
5-8	10	1.8	0.3, 1, 3, ∞

Comparison of simulated breakthough curves (Figs.4a and b) with those observed from the field tracer test (Fig.4c) suggest that the Chalk shows behaviour characteristic of connected fracture advection-dispersion with matrix diffusion. The observed slow fall in post-peak tracer concentration with time (Fig.4c) suggests that the smallest hydraulic block size used (0.3m), combined with the lower fracture porosity (0.01%) provides the best match to observed behaviour for curve shape (compare run 1 in Fig.4a with Amino-G acid curve in Fig.4c). This is the model with the largest diffusion effect. However, model run 1 produced a peak breakthrough time of 1.4 hours compared with tracer test values of 50 and 31 hours. When allowance is made for the lower pumping rate of the test ($330m^3$/day) than in the simulations ($690m^3$/day), an average fracture porosity of 0.1 to 0.2% and a hydraulic block size of around 1m is indicated (see Moench 1995, for a full explanation). This average fracture porosity is consistent with flowing fracture apertures of 1-2 mm at 1m fracture spacing, or 0.1-0.2 mm apertures at 10 cm spacing. Such large apertures could be indicative of flow in brecciated zones within the Chalk. Further modelling will focus on flow in thin highly fractured layers, and inclusion of fracture skin effects and source functions more representative of the tracer test.

CONCLUSIONS

The discrete fracture model shows that at natural flow rates in unconnected fracture systems, diffusion from fractures into matrix can significantly enhance contaminant transport, even when fracture apertures are small (120 μm). The dual porosity model suggests that there is a significant effect from matrix diffusion, and that fracture porosity is around 0.1-0.2% . This corresponds to apertures of the order of 1-2 mm for fractures spaced at 1 m, to 100-200 μm at 10 cm fracture spacing. This suggests that very highly fractured or brecciated horizons dominate the flow.

ACKOWLEDGEMENTS

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REFERENCES

Atkinson TC, Ward RS, O'Hannelly E (2000) A radial flow tracer test in Chalk: comparison of models and fitted parameters. In – Tracers and Modelling in Hydrogeology, IAH Publ. No 262:7-15

Garnier JM, Crampton N, Preaux C, Porel G, Vreulx M (1985) Tracage Par ^{13}C, ^{2}H, I^- et Uranine dans la Nappe de la Craie Senonienne en ecoulement radial convergent (Bethune, France). Journal of Hydrology 78:379-392

Grisak GE, Pickens JF (1980) Solute transport through fractured media 1. The effect of matrix diffusion. Water Resources Research 16:719-730

Barker JA, Foster SSD (1981) A diffusion exchange model for solute movement in fissured porous rock. Q F.eng Geol London 14:17-24

Moench AF (1995) Convergent radial dispersion in a double-porosity aquifer with fracture skin: Analytical solution and application to a field experiment in fractured chalk. Water Resources Research 31:8:1823-183

HyTests: a set of numerical models for hydrogeologic parameters estimation

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A b s t r a c t : HyTests is software that is used to assist in the estimation of formation hydraulic parameters. Currently, HyTests is capable of describing three hydrogeologic models: homogeneous formations (1D Finite-Difference radial flow); horizontally-heterogeneous flow (2D Finite-Element model); and hydraulically interconnected fractures (2D Finite-Element disks, set in a 3D space). After HyTests was successfully validated, a sensitivity analysis was conducted to delineate the comparative relevance of each hydrogeological parameter on the modeled responses. HyTests was used extensively to analyze hydraulic tests at a fractured bedrock formation.

HyTests is a JAVA application used for interpretation of Hydraulic Tests (HT) (Pumping Tests (PT) or Slug Tests (ST)) field data. It is a tool for the hydraulic characterization of a formation in terms of hydrogeologic units, hydraulic parameters, and boundary conditions. HyTests has assisted the hydrogeological evaluation of a fractured bedrock formation. It can be downloaded at www.bbc.unh.edu.

1D Finite–Difference radial-flow model simulates time-drawdown HT curves in homogeneous formations for any input hydrogeologic parameter data set (Rushton 1979). Simulated results are graphically displayed, and statistically compared with field data; they can be interactively updated until satisfactory fitness is attained. Actual PT conditions, such as variable-flowrate and well hydraulic loss, are supported. The model was successfully tested with published examples of the Theis, Jacob, Hantush, and Papadopolus methods (PT), and Hvorslev and Cooper methods (ST) (Fig.1).

2D Finite–Element model analyzes HT in horizontally–heterogeneous formations (Istok 1989.) It significantly improves the reliability of hydrogeologic parameter estimation when HT curves at different Monitoring Wells (MW,) follow different trends. That is the expected case when testing formations with appreciable spatial variability, or subjected to boundary effects. This model was also used on interpretation of Large Displacement Slug Tests (LDST) (Pulido–Silva *et al.* 2003a).

A Fracture – Network model analyzes discrete fractures as interconnected disks in the 3D space (Adler *et al.* 1999). Each disk is represented by using 2D Finite– Elements. This model allows the analysis of discrete-interval HT, in which targeted well zones are isolated at the Stressed Well (SW) (pumped well (PT), slug-applied well (ST)) and MW; then, hydraulic responses are recorded at discrete intervals of SW and MW.

A sensitivity analysis was conducted for the three models. Numerical stability, and comparative relevance of each hydrogelogic parameter on the simulated response were studied, as well as spatial variability thresholds of the hydrogeologic parameters where a heterogeneous formation can be accurately represented by a homogeneous model.

HyTests was developed to assist the hydraulic characterization of a fractured-bedrock metamorphic formation contaminated with chlorinated solvents. This intensive HT program included more than 20 PT, more than 200 ST, and more than 200 LDST. The three HyTests models were progressively applied to improve the hydraulic understanding of the study site, and results of each model were dynamically used into the specification of the next steps of the HT program (Pulido–Silva *et al.* 2003b) (Fig.2).

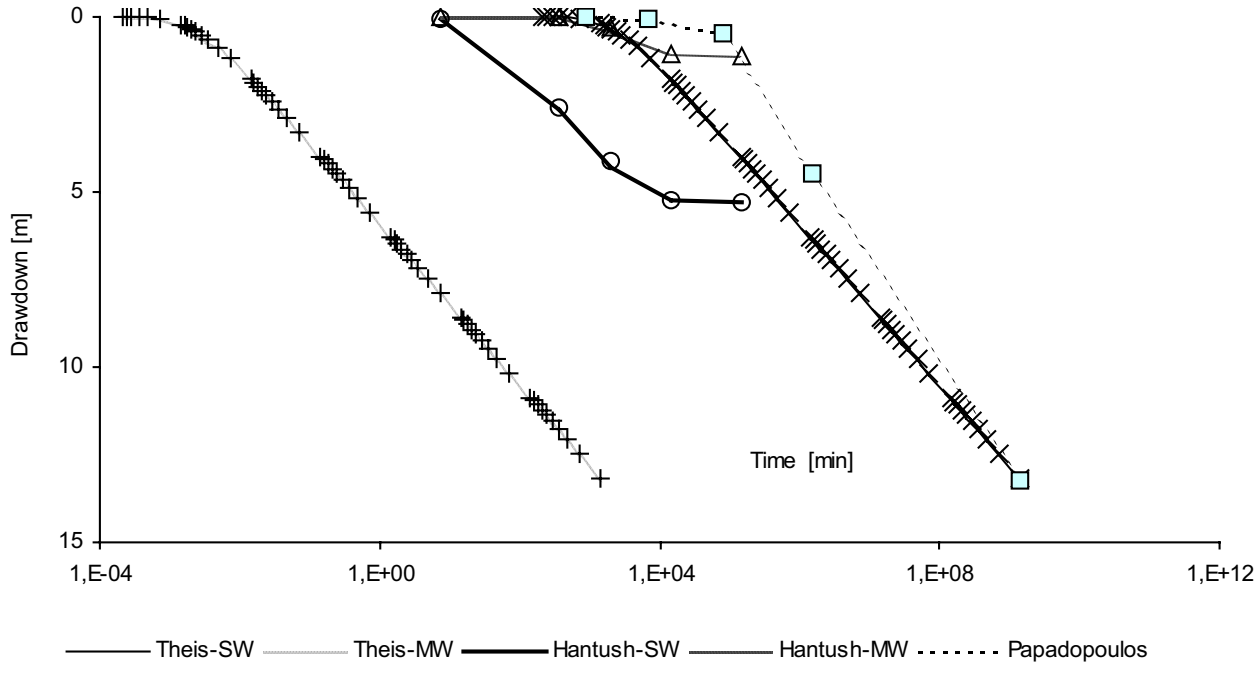

Figure 1. HyTests validation with PT analytical models (markers are HyTests homogeneous model results)

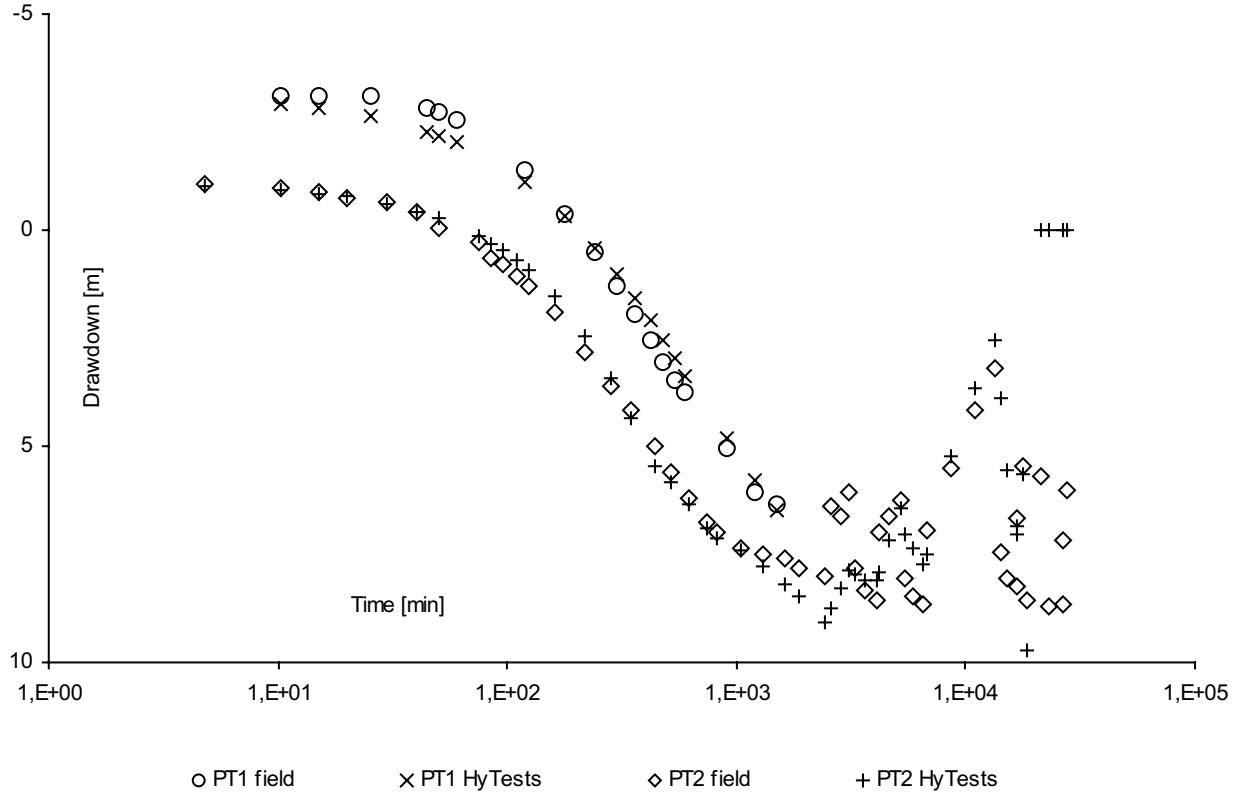

Figure 2. Drawdown - time curves (Field data and HyTests modeled) for two single-well PT conducted at a low-yield well (BBC1) with unstable flowrate (PT1 isolated interval. = 14.35 – 15.85 m; HyTests estimated parameters: hydraulic conductivity (K) = 0.09 m / day; Storage Coefficient (S) = 1E-4. PT2 isolated interval = 12.55 – 14.05 m; HyTests estimated parameters: K = 0.01 m / day; S = 1E-4)

HyTests will be extended by adding two more models, and linking the Fracture – Network model with fracture–analysis software. A layered-Heterogeneous model will allow HT interpretation on porous–media stratified formations represented by 2D Finite– Element parallel disks. A 3D Finite– Element model will take into account any spatial specification of the hydrogeologic parameters, and to assess their influence on HT interpretation. The Fracture– Network model will be enabled to communicate with fracture–analysis models to test fracture distributions fitness to HT field data.

REFERENCES

Adler PM, Thovert JF (1999) Fractures and fracture networks, 1st edition. Kluwer Academic Publishers, Dordrecht, 429 pp

Istok J (1989) Groundwater modeling by the finite element method, 1st edition. American Geophysical Union, Water Resources Monograph 13, Washington, DC, 495 pp

Pulido–Silva G, Ballestero TP, Kinner NE (2003b) Large displacement slug tests. In: IAH International Conference on Groundwater In Fractured Rocks–Proc

Pulido–Silva G, Ballestero TP, Barrera MI, Marbet HJ, Kinner NE (2003a) Developing a conceptual hydrogeological model for a fractured bedrock formation. In: IAH International Conference on Groundwater In Fractured Rocks–Proc

Ruston KR, Redshaw SC (1979) Seepage and groundwater flow, 1st edition. John Wiley & Sons, Norwich, 339 pp

A methodology for solving the inverse flow and transport problem in discrete fracture networks

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A b s t r a c t : A methodology for simulating groundwater flow and solute transport in discrete fracture networks (DFN) is presented. The methodology starts from a DFN of 2-D bodies (disks) embedded in a 3-D field. The interconnections between these bodies define a conductive matrix, represented by 1-D elements.. The parameters at each element are obtained from a predefined statistical distribution that takes into account the fracture family that each disk initially belonged. This allows having a manageable number of parameters to calibrate when using the inverse problem. The same methodology has been extended to account for groundwater transport. An application of the methodology to interpret actual hydraulic and tracer tests performed in a site in Spain is shown.

MOTIVATION AND OBJECTIVES

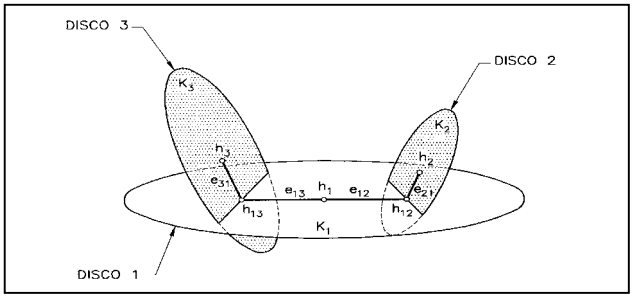
The study of fracture networks in low permeability media (e.g. granite massifs) is of outmost importance due to the possibility of locating radioactive waste disposal sites. Deterministic characterization of fractures in a real batholith is virtually impossible. Therefore several alternatives are available. The two extreme cases are equivalent porous media models and discrete fracture networks. Among the advantages of DFN is their resemblance to reality and the possibility of including some feature of reality without the need to upscale either processes or parameters. The resemblance to reality should be considered in a statistical sense, as it is impossible to fully characterize the fracture network. One drawback is the difficulty in conditioning the DFN with the actual knowledge of the fracture location. A second drawback is the difficulty to properly define a methodology for parameter estimation using the inverse problem with data coming from hydraulic or tracer tests.

The objective of the paper is to present a hydrogeological simulation methodology of fracture media based on DFN models, but allowing parameter estimation. The general idea is to extent the methodology of Cacas *et al.* (1990) of finding the conductive matrix formed by 1-D elements to substitute the actual DFN, but doing it such that the association of any given element to a fracture family is maintained. This way only a (small) finite number of parameters, associated to families, are to be estimated. The methodology has been successfully applied to interpret pumping and tracer tests performed and already interpreted using a equivalent approach at El Berrocal Site.

SIMULATING FLOW AND TRANSPORT IN DFN

Definition of the conductive elements in DFN face two important problems (Long *et al.* 1982): (1) geometrical, as DFN require choosing a number of statistical distributions in order to define for each fracture its location, orientation, length (or geometry), aperture and transmissivity; and (2) numerical, while solving the PDE's governing groundwater flow and solute transport.

The methodology presented here is a modification of the channel model developed by Cacas *et al.* (1990). The starting point is a network of fractures (disks embedded in a 3-D domain) generated externally. The definition of the DFN includes geometry and hydraulic parameters for each individual fracture, plus and indication to the family each individual fracture belongs (this last point being of outmost importance in our methodology). The concept of channeling implies that despite the fracture is modeled as a disk, actual flow takes place only in a small part of it, that is in channels associated to the most conductive features within a given fracture. The most critical point is the way these channels are interconnected, forming a 3-D network of 1-D elements. A simplified way to consider channels is represented in Fig.1 (top). Note that one of the advantages of this metho-dology with respect to that of Cacas *et al.* (1990) is that with this scheme each element still belongs to a given disk, and therefore it is possible to associate each element to a given fracture family.



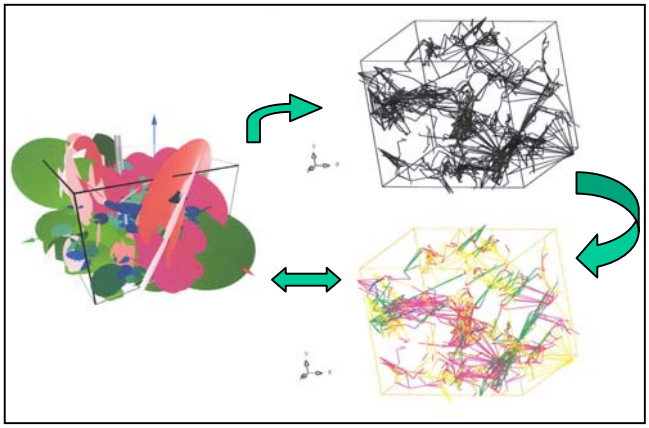


Figure 1. Constructing the conductive network. Top: from individual fractures to 1-D elements. Bottom: Going from a 3-D DFN to a mesh of 1-D elements. Colors represent families

The parameters associated to any given 1-D element are transmissivity (T) and storativity (S). Each element is associated a parameter which is equal to the product of two terms: (1) a specific value that comes from a statistical distribution a priori (e.g. a lognormal distribution for T), and (2) a scaling factor (zone

parameter) which is an unknown value, the same for all elements associated to a given family. The latter value is the one calibrated by means of the inverse problem; thus, only a reduced number of parameters (one or two per family) are to be estimated. An example of the full procedure of going from a DFN to a mesh formed by 1-D elements while keeping the concept of fracture family is presented in Fig.1 (bottom).

Regarding boundary conditions, they must be applied to all elements that intersect a given external volume used in the definition of the DFN. This can be done by using a given geometry (e.g. parallelepiped) and associating a boundary condition (constant head, constant flow or mixed) to every face.

An important point is that not all 1-D elements are connected. Actually there is only some portion of the elements that form the conductive matrix. A requisite for an element to be significant hydrogeologically is that a path could be found so that it is connected with the boundary. This way the non-connected clusters of elements should be removed before any calibration procedure is attempted in order to reduce CPU time.

Calibration is done using TRANSIN (Medina *et al.* 1996). The code requires observed values of heads and or concentrations at some points (observation points) and estimates the parameters that best fit the observed values. Observation points should belong to an element which is part of the conductive network. Observation points are associated to the closest point in the mesh.

The methodology for transport is similar, but it includes some additional parameters that should also be associated to any given element: porosity, molecular diffusion, longitudinal dispersivity, retardation coefficient, first-order radioactive decay and matrix diffusion. These values are also associated to families, despite any given element could have a different coefficient drawn from an a priori statistical distribution (e.g., porosities). Boundary conditions have to be applied to all elements reaching the boundaries. Initial conditions can be either a fixed mass or entering the system as an external flux with a given concentration.

In this type of meshes numerical instabilities can cause both the direct and(or inverse problems not to converge. This might call for reducing the length of the elements, therefore increasing the number of nodes, which leads again to CPU problems.

EXAMPLE

A synthetic example is now shown aimed at illustrating the methodology presented. The example comprises the interpretation by means of DFN of a pumping and a tracer test carried out in the framework of the El Berrocal Project (Rivas *et al.* 1997)

The DFN was modeled as defined by 6 fracture families. Each family is defined by the number of fractures, and their individual location, orientation and fracture aperture, each parameter drawn from a predetermined statistical distribution. The block simulated was 400x400x350 m. A pumping test was simulated and the interpretation was performed using the methodology presented in this paper. Boundary conditions applied in the numerical model where no flow in the top and bottom boundaries and zero drawdown elsewhere. The calibrated parameters where a single value for T and S for each independent fracture family, leading to a total of 12 parameters for estimation. The results of the calibration process can be seen in Fig.2. The match between computed and observed drawdowns is similar to the one that was obtained in Rivas *et al*. (1997) applying a continuous equivalent approach, indicating that the methodology presented could compete in terms of data matching.

The methodology was then extended to transport. Boundary conditions for transport where that no concentration was leaving the domain. A double porosity modeled was considered. Processes modeled where advection, dispersion and matrix diffusion. The total number of estimated parameters was four (two porosities, two dispersivities corresponding to the mobile and immobile zones) The match between observed and computed concentrations at the extraction point is acceptable and also comparable with the one obtained using an equivalent porous media for conceptualization (Fig.3).

We conclude that the methodology presented allows calibrating the parameters corresponding to a DFN obtaining matches qualitatively and quantitatively as good as those obtained using a conceptual model of an equivalent porous medium. The definite advantage of the method is that the DFN simulated is not unique, and therefore this methodology is easily and immediately casted in a geostatistical framework, and therefore it is easier to find a physical meaning to the calibrated values

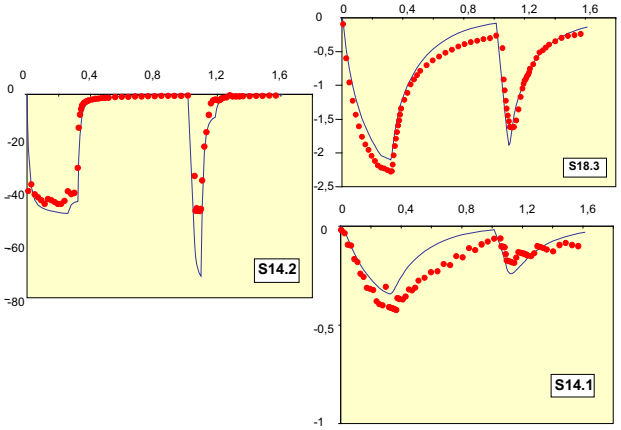


Figure 2. Observed (red dots) vs. computed drawdowns (blue lines) after calibration of a pump test (pumping in S14.2, plus two observation points) in El Berrocal using a DFN approach. Time in days.

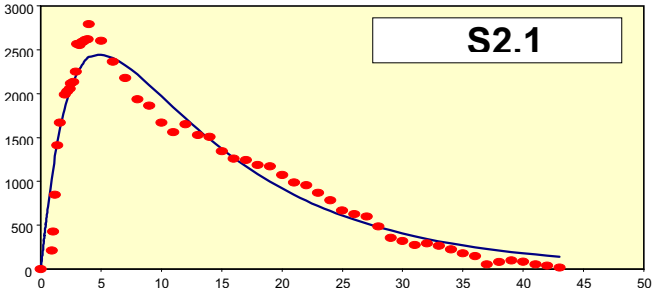


Figure 3. Observed (red dots) vs. computed (blue lines) concentrations (in ppb) at the sampling point after calibration of a tracer test in El Berrocal using a DFN approach. Time in days. Tracer is uranine

Acknowledgements

The work has been carried within the framework of Hidrobap-II, a multidisciplinar project aimed at characterizing fractured media both structurally and hydrogeologically by means of DFN.

REFERENCES

Cacas MC, Ledoux E, de Marsily G, Tillie B (1990) Modelling fracture flow with a stochastic discrete fracture network: calibration and validation. 1: The flow model. Water Resources Research 26:479-489

Long JCS, Rewer JS, Wilson CR, Whitherspoon PA (1982) Porous media equivalents for networks of discontinous fractures. Water Resources Research 18(3):645-658

Medina A, Galarza G, Carrera J (1996) TRANSIN II. Fortran code for solving the coupled flow and transport inverse problem in satured conditions. Topical report 16, volume IV, El Berrocal Project, EC Contract FI2W/CT91/0080

Rivas P, Hernán P, Bruno J, Carrera J, Gómez P, Guimerà J, Marín J, Pérez del Villar L (1997) El Berrocal Project. Characterization and validation of natural radionuclide migration processes under real conditions on the fissured granitic environment. Final Report. EC Contract FI2W/CT91/0080

Solute transport in crystalline rocks with fracture skins

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A b s t r a c t : Fracture skins are layers along fracture surfaces that consist of microfractures, alteration zones, or coatings; they change the rock's hydraulic and transport properties. Skins tend to be higher in porosity and sorptive capacity than the unaltered rock. We evaluate solute transport with mathematical analyses of steady and transient flows with both pulse and step source functions for both reactive (e.g., Cs^{137}) and conservative (e.g., Cl^{-1}) tracers. Sensitivity factors for skin thickness, porosity, diffusion coefficient, sorptivity (expressed as retardation coefficient), and fracture aperture compare the effects and demonstrate that skin diffusion coefficient and porosity are the most critical factors. For a wide range of fracture properties, skin thickness are important and that retardation of solutes can be significant for crystalline rocks where the fractures possess skins. Back-diffusion is an important process in controlling the solute concentrations. These factors create uncertainty for tracer tests to infer flow velocities in crystalline rocks.

INTRODUCTION

Flow and transport in fractured media is of interest in connection with groundwater contamination problems and in performance assessment of reservoirs and potential waste disposal sites. Fractures are ubiquitous and serve as preferential flow paths to enhance contaminant migration in low permeability crystalline rocks. Fractured crystalline rocks may be grouped into purely fractured or fractured formations, depending on hydraulic conductivity and storativity of fracture relative to the matrix (Streltsova 1976; Sharp 1993). Fracture skins may be present in any of these media and alter their hydraulic and transport properties. Fracture skins can be defined as "a thin layer or coat on and just underneath a fracture surface, which is caused by precipitated and deposition of secondary minerals and possibly biogenic materials" (Fu *et al.* 1994), or "zones of altered rock abutting the fracture and the coatings of the fracture surfaces by infiltered debris and precipitated minerals and organic matter" (Robinson and Sharp 1997). The alteration can be physical and consist of a damage zone with microfractures. A wide range of coatings are observed including carbonates, case hardening agents, dust film, metal oxides, iron films, lithobiotic matter, nitrate crusts, oxalate crusts, phosphate skins, pigments, rock varnish, salt crusts, silica glaze, and sulfate crusts (Dorn 1998; Fu *et al.* 1994; Fuller and Sharp 1994; Weisbrod *et al.* 1999). Hydrogeologic properties of fracture skins (i.e., permeability, porosity, sorptivity, and diffusion coefficients) may differ from those of the matrix. Skins influence solute exchange between fracture and rock matrix and transport processes of the fracture flow system.

CRYSTALLINE ROCK SKINS

Fractures in crystalline rock are ubiquitous and serve as preferential flow paths. The fracture skins are in the form of microfractures or micropores, and, at normal flow gradients, solutes can enter the void spaces by way of diffusion. Skagius and Neretnieks (1986) showed variation in the diffusion coefficient when comparing different types of crystalline rocks. In granites, fracture diffusion coefficients are higher in the skin than in the rock matrix and porosity within the rock matrix is generally lower than that of fracture skins. In crystalline rocks coatings in the form of silica glaze, precipitated minerals, infiltered debris, or organic matter are common (Dorn, 1998). The fractures that conduct fluids are the fractures that will posses skins.

MODEL

The mathematical model analyzes the effects and sensitivity of fracture skins on solute transport. Previous studies (Kreisel and Sharp 1996; Landrum 2000; Robinson and Sharp 1997, and Robinson *et al*. 1998) considered a continuous step source function; this study evaluates both continuous step and rectangular pulse source functions. Depending on the source, characteristics of solute concentrations and flow system in the fractures may be different. Chloride (Cl) and cesium (^{137}Cs) are used as the conservative and reactive ions to analyze sorption and radioactive decay.

We consider systems of parallel fractures of uniform aperture (2b) separated by a distance of 2H. The fractures are L in length. The skin thickness is d - b. Three differential equations for fracture, fracture skin, and matrix concentrations (C_f, C_s, and C_m, respectively) are solved:

Fracture:

$$\frac{\partial^2 C_f}{\partial z^2} - \frac{v}{D_f}\frac{\partial C_f}{\partial z} - \lambda\frac{R_f C_f}{D_f} + \frac{\phi_s D_s}{bD_f}\frac{\partial C_s}{\partial x}\bigg|_{x=b} = \frac{R_f}{D_f}\frac{\partial C_f}{\partial t}$$

Skin:

$$\frac{\partial^2 C_s}{\partial x^2} - \lambda\frac{R_s}{D_s}C_s = \frac{R_s}{D_s}\frac{\partial C_s}{\partial t}$$

Matrix:

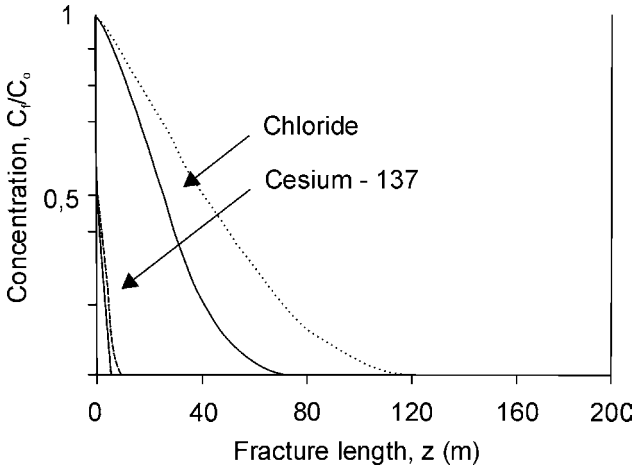
$$\frac{\partial^2 C_m}{\partial x^2} - \lambda\frac{R_m}{D_m}C_m = \frac{R_m}{D_m}\frac{\partial C_m}{\partial t}$$

Where z is distance along the fracture and x is distance into the skin and rock matrix. D_f is the Taylor dispersion coefficient (Taylor 1953; Aris 1956); D_m and D_s are diffusion coefficients in the matrix and skin; R_f, R_s, and R_m are the retardation coefficients for the fracture surface, skin, and matrix; λ is the decay coefficient; and ϕ_s is skin porosity. Transient and steady-state solutions, obtained from Laplace transform and residue analyses are presented in Robinson and Sharp (1997) and Robinson *et al.* (1998) for the step function and modified for transient pulse function in Phyu (2002). In crystalline rocks, R_m, D_m, and porosity can be so small that they approach (are set to) zero in the analyses.

RESULTS

The results of the analytical transient solutions used the numerical inversion of the Laplace transform (Piessens and Huysmans 1984) documented by Robinson and Sharp (1997) to provide very precise approximations of the analytical series solutions. Digital Visual FORTRAN (1998) software was used and a FORTRAN program for sensitivity analyses is available in Phyu (2002). Analyses included the effects of fracture skins, time, fracture length, and fracture aperture. Scenarios considered with Cl and ^{137}Cs, and step and pulse (on the order of 100 days) functions.

Fig.1 shows one of the many sensitivity analyses for a fractured rock with a skin that is porous relative to the unaltered rock matrix. The skins retard the solute transport for both reactive and conservative solutes. In the pulse model, skins provide a long-term release source by back- diffusion.



CONCLUSIONS

Fracture skins in crystalline rocks can significantly affect solute transport. These skins are commonly more porous than the matrix; solutes are retarded by diffusion into the skins. Reactive solutes are transported at lower rates than conservative solutes, and skin effects are muted because of retardation and decay. When solute input is a pulse, back-diffusion can be important. After the solute front passes, the concentration in the fracture can be higher than expected due to back-diffusion. In addition to diffusion, retardation, and decay, fracture length and aperture are shown to control solute residence in the fracture and breakthrough concentrations.

Sensitivity analyses suggest that skin porosity and diffusivity are the most important parameters followed by sorptivity for reactive solutes and skin thickness and fracture aperture for conservative solutes. Variations in skin porosity and diffusion result in the greatest change in solute concentration in the fracture. When these parameters are small, the rates of diffusion into the skin and matrix are limited, but Taylor dispersion still operates and a plug-flow condition is reached. When several parameters are altered simultaneously, the effect of skin thickness is small compared to other parameters. Generally, solute concentration in the fracture decreases with increases in skin porosity, diffusivity, and sorptivity. In all analyses, skin porosity was shown to be the most significant parameter Thus, it should be carefully estimated.

Transport of either reactive or conservative solutes in fractured crystalline rocks can be significantly affected by the fracture skins.

REFERENCES

Aris R (1956) On dispersion of a solute in a fluid flowing through a tube. Proc Royal Society London, Series A 235:67-77

Digital Visual Fortran (1998) Digital Equipment Corporation

Dorn RI (1998) Rock Coatings, Elsevier, Amsterdam, 429 pp

Fu L, Milliken KL, Sharp JM Jr (1994) Porosity and permeability variations in fractured and liesegang-banded Breathitt sandstones (Middle Pennsylvanian), eastern Kentucky; diagenetic controls and implications for modeling dual-porosity systems. J Hydrology 154:351-38

Fuller CM, Sharp JM Jr (1994) Permeability and fracture patterns in extrusive volcanic rocks: implication from the welded Santana tuff. Trans Pecos Texas Geol Soc America Bull 104:1485-1496

Kreisel I, Sharp JM Jr (1996) Fracture skins in the Brushy Canyon Formation. In: DeMis WD, Cole AG (eds) The Brushy Canyon play in outcrop and subsurface: Concepts and examples, PBS-SEPM 96-38:147-152

Landrum MT (2000) Hydrogeologic properties of fracture skins and their effects on radionuclide transport, unpub MS thesis, Univ Texas, 133 pp

Phyu T (2002) Transient modelling of contaminant transport in dual porosity media with fracture skins, unpub. MS thesis Univ Texas 125 pp

Piessens R, Huysmans R (1984) Algorithm 619, Automatic numerical inversion of the Laplace transform. ACM Trans Math Software 10:348-353

Robinson NI, Sharp JM Jr (1997) Analytical Solution for Solute Transport in a Finite Set of Parallel Fractures with Matrix Diffusion, CSIRO CMIS Rpt C23/97, 23 pp

Robinson NI, Sharp JMJr, Kreisel (1998) Contaminant transport in sets of parallel finite fractures with fracture skins. J Contam Hydrology, 31:83-109

Sharp JM Jr (1993) Fractured aquifers/reservoirs; Approaches, problems, and opportunities. In: Banks D, Banks S (eds) Hydrogeology of Hard Rocks, Memoires Int Assoc Hydrogeologists, Oslo, 24(1):23-38

Skagius K, Neretnieks I (1986) Porosities and diffusivities of some nonsorbing species in crystalline rocks. Water Resources Research 22:389-398

Streltsova TD (1976) Hydrodynamics of groundwater flow in a fractured formation. Water Resources Research 12:405-4 13

Taylor G (1953) Dispersion of soluble matter in solvent flowing slowly through a tube. Proc Royal Society London, Series A, 219:186-203

Weisbrod N, Nativ R, Adar EM, Ronen D (1999) Impact of rainwater and wastewater flow on coated and uncoated fractures in chalk. Water Reso urces Research 35:3211-3222

The verification and the further development of a method for the determination of the spatial distribution of heterogeneities based on numerical simulations

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A b s t r a c t : An approach to identify the macro-scale permeability distribution by using multiple tracer measurements, multivariate statistics and numerical simulation is presented. The use of the numerical simulation serves three different purposes. First, the verification of the permeability distribution deduced from measurements. Second, improvement and further development of the applied multivariate statistical approach. Third, the enhanced understanding of the influence of heterogeneities on tracer breakthrough curves. The method is demonstrated for measurements made on a bench scale sandstone block.

INTRODUCTION

The determination of the spatial distribution of material properties in strongly heterogeneous media is a challenge, due to the fact that common measurement techniques yield integral results. A possibility to obtain an extended information basis, is to perform a larger number of measurements, in total covering the total area of interest, and to spatially arrange them so that comparability between the single measurements is given. By means of multivariate statistics, the measurements are clustered into groups of similar characteristics, indicating the location of regions possessing similar material properties. Such measurements, in this case the detection of the response to a tracer impulse, were performed on a heterogeneous air saturated bench scale (60cm) sandstone block as presented by Brauchler *et al.* (2003). Here, it will be discussed how the classified tracer breakthrough curves can serve as a basis for the determination of the permeability distribution of the block.

APPROXIMATION OF THE PERMEABILITY DISTRIBUTION USING CLASSIFIED MEASURED TRACER BREAKTHROUGH CURVES

Experimental set-up

On each of the six sides of the investigated cubical (60x60x60cm) air saturated sandstone block, 16 measurements ports are mounted in a regular pattern whereas the rest of the surface is sealed. During a measurement only two ports, always located directly opposite to each other, are open. A pressure of p_1 = 1.5 bar and p_2 = 1.0 bar is imposed to the in- and to the outflow ports, respectively. After steady state flow conditions are reached, a tracer pulse is injected and the concentration is measured at the outflow port. This procedure is repeated for all port configurations, yielding a collection of 16x3 tracer breakthrough curves. A detailed description is found in Brauchler *et al.* (2003).

Classification of the measured tracer breakthrough curves

For each of the measured tracer breakthrough curves, the discharge and certain characteristic values describing the shape of the curve are determined. A factor analysis is performed to determine a number of almost uncorrelated variables, used to classify the curves. The classification is performed by means of a k-means cluster analysis. A detailed description is given in Brauchler *et al.* (2003). Before the classification can be carried out, the curves must be divided into groups according to the location of the ports relative to the block boundaries, to obtain comparability. The effect of the boundaries on the shape of the tracer breakthrough curve is of significant importance (Eichel 2002). Currently, detailed investigations concerning the quantitative influence of boundaries on tracer breakthrough curves and on their sensitivity to heterogeneities are being performed. In fig.1, the classified tracer breakthrough curves of all port configurations located in the corners of the block (4x3) are shown. Here, these curves serve as a basis for discussion of the method.

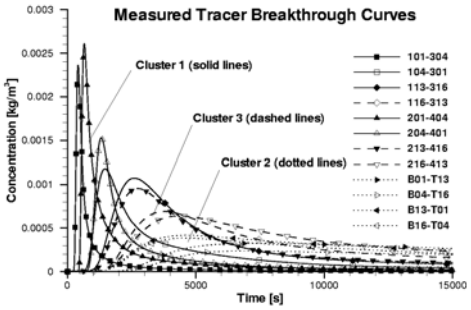

Figure 1. Clustered measured tracer breakthrough curves

Three clusters are obtained from the analysis. The port configurations of the curves belonging to cluster one are almost all located in the upper corners of the vertical sides of the block (101-304, 104-301, 201-401 and 204-401). Additionally, configuration (113-316) is included into this cluster. However, visual inspection of the plotted curves (fig.1) lead to the conclusion, that this curve seems to be closer to cluster three than to cluster one. Currently, the aspect of achieving a satisfying and meaningful cluster result is investigated using numerical simulations, as briefly discussed in the last chapter of this paper. Cluster three is formed by curves located in the lower corners of the vertical sides of the block and cluster two is formed by the corner configurations for the bottom-top measurements. The curves of cluster one show a sharp increase in concentration and an early initial arrival time. On the contrary, the curves of cluster two arrive late and are very widely spread. The curves of cluster three show an intermediate behaviour. Based on these observations it is assumed that the block consists of two horizontal layers of different permeability, where the upper layer is more permeable than the lower one. Since the mean arrival time of cluster two is the largest, it is further assumed that there is an anisotropy factor larger than one between the horizontal and the vertical direction. The location of the boundary between the upper and the lower layer cannot be determined exclusively from the 12 measurements shown in this example, but prior knowledge is applied.

Approximation of the permeability distribution

The permeability k is approximated based on Darcy's law, using the mean initial arrival time of each cluster $\bar{t}_{init}$, known values of the pressure p and of the dynamic viscosity μ, assumed values of the porosity ϕ and of the length of the flow path L, according to the following expression:

$$k = \frac{L^2 \cdot \phi \cdot \mu}{\bar{t}_{init} \cdot (p_1 - p_2)} \qquad \text{(Eq.1)}$$

The use of $\bar{t}_{init}$ is based on the assumption that the initial arrival time represents the portion of the tracer mass travelling the shortest distance. Due to dispersive and diffusive effects, this overestimates the determined permeability. Currently, using numerical simulations, the correct choice of a representative time for different situations is investigated (see "Final remarks and outlook"). To a certain extent this overestimation is compensated by the fact that the direct distance (60cm) is not equal to the length of the shortest flow path between two ports. Due to the influence of the boundaries, the actual length is larger.

The permeability k calculated according to equation 1 estimates the effective permeability between two ports. Therefore, for cluster two (bottom-top), the estimated permeability is the harmonic mean of the permeabilities of the upper and the lower layer, under consideration of an anisotropy factor. The anisotropy factors for the two layers are determined by comparison of the estimated permeabilities in the x,y-direction and the permeability according to equation 1 for cluster two. This procedure yields the permeabilities presented in tab.1.

Table 1. Estimated permeability based on classified measured tracer breakthrough curves

Direction	Permeability k [10^{-14} m^2]	
	Upper layer	Lower layer
x,y	4.0	2.0
z	2.5	1.3

NUMERICAL SIMULATION

Model set-up

A three-dimensional model is set up, using the known boundary geometry of the experimental block, known fluid parameters of air, the assumed porosity and the permeability distribution deduced from the results of the cluster analysis. The diffusion coefficient as well as the transversal and longitudinal dispersivities are minimised with the objective to emphasise the advective transport process. For each port configuration, a mesh with refinement around the in- and the outflow ports is generated using the mesh generator ART (Fuchs 1999). The boundary conditions for the flow and for the transport simulation, are chosen with the objective to achieve the best possible compliance with the real experiment. Investigations of the influence of compressibility show that this aspect must be considered. This aspect is implemented into the numerical model, based on the universal gas law. The simulation is performed using the numerical simulator MUFTE_UG (Helmig *et al.* 1998).

Discussion of the simulation results

The simulated tracer breakthrough curves are classified by means of the cluster analysis under equal conditions as for the measured ones, allowing a direct comparison between the two sets of clusters. In fig.2 the classified simulated tracer breakthrough curves are presented.

Three very distinct clusters are found. The first cluster is characterised by an early average arrival time and a sharp concentration increase. The curves of the second cluster arrives late and have a pronounced tailing. The third cluster takes an intermediate position. Comparing the measured result with the simulated one, lead to the following conclusions: (1) the initial arrival time of all the corresponding clusters show good agreement, (2) the arrival of the peak of the simulated curves is generally slightly earlier than for the measured ones, (3) the simulated peak concentrations are generally overestimated, (4) the spreading of the simulated curves of cluster two and three is underestimated.

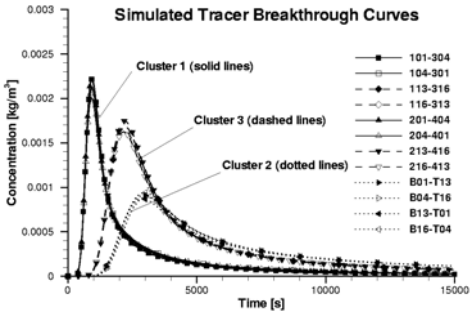

Figure 2. Clustered simulated tracer breakthrough curves

The relatively good compliance of the initial arrival time (1) combined with the slightly early peak time (2) indicate that, on average, the estimated permeability distribution is plausible, however somewhat overestimated. Observation (3) and (4) both indicate a more significant effect of dispersion and diffusion processes for the real block. This deviation from the measured curves is expected, since the advective processes are deliberately pronounced in the simulation set-up. Another general observation, made from the comparison of the characteristic parameters used for the classification of the curves, is that the variation for the simulated curves within each cluster is almost negligible. This is of course a consequence of the assumption that the two layers are homogeneous. Small-scale heterogeneities lead to stronger variation and a more pronounced tailing.

FINAL REMARKS AND OUTLOOK

The study shows that it is possible to determine the distribution of macro-scale heterogeneities using multiple tracer measurements, multivariate statistics and numerical simulation. However, there is no guarantee that the estimated distribution is unique. Moreover, there are still a number of issues that need further investigation in order to improve the method and to test the feasibility for different types of heterogeneity distributions. Currently, investigations dealing with these issues are being performed. For this purpose fictitious cases are designed, the first with block shaped heterogeneities, the second with a few fractures, the third with a regular fracture system and the fourth with a natural fracture system. All fracture systems are embedded in a porous matrix. One person simulates the "measured" tracer breakthrough curves and another person, without knowledge about the structure of the domain, deals with the evaluation of these curves. The use of numerical models, for which the exact permeability is known, yields the possibility to assess the quality of the results. It is expected, that the use of the multivariate statistics methods can be optimised and that the method for determination of the permeability distribution can be improved.

REFERENCES

Brauchler R, Leven C, Dietrich P (2003) Multivariate statistical approach for characterizing flow and transport processes. In: The proceedings of this conference

Eichel H (2002) Investigation of boundary influences on flow and transport in porous media. M.Sc. thesis, University of Stuttgart

Fuchs A (1999) Optimierte Delaunay-Triangulierungen zur Vernetzung getrimmter NURBS-Körper. Ph.D. thesis, University of Stuttgart

Helmig R, Class H, Huber H, Sheta H, Ewing R, Hinkelmann R, Jakobs H, Bastian P (1998) Architecture of the modular program system MUFTE_UG for simulating multiphase flow and transport processes in heterogeneous porous media. Mathematische Geologie 2

Applying the multi-continuum approach to experimental data of tracer experiments in fractured permeable sandstone

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A b s t r a c t : This contribution focuses on the possibilities and limitations of multi-continuum models with regard to simulating flow and transport in fractured porous media. In particular, the sensitivity of model results due to variations in coupling and transport parameters as well as flow conditions (saturated / unsaturated) is studied. This is done by comparing model results with experimental data obtained from laboratory scale tracer tests.

OBJECTIVE

Investigations concerning fractured formations often focus on their potential as hydraulic barriers with regard to nuclear waste deposits, whereas the presented study focuses on contaminant transport in fractured aquifers with considerable fracture and matrix permeability, respectively. However, the fracture network and the rock matrix are the two main heterogeneous hydraulic components of such formations. For some formations more than these two main components have to be distinguished such as a macro- and micro fracture system. Multi-continuum models are applied to simulate contaminant transport in such formations. Central to those models is the assumption that the heterogeneous rock formation can be separated into coupled homogeneous media, each representing one hydraulic component. Essential to the principle on homogenization for heterogeneous media is to define equivalent model parameters and to find appropriate formulations for the interaction of the hydraulic components, capable of describing the correct physical system behavior (see fig.1).

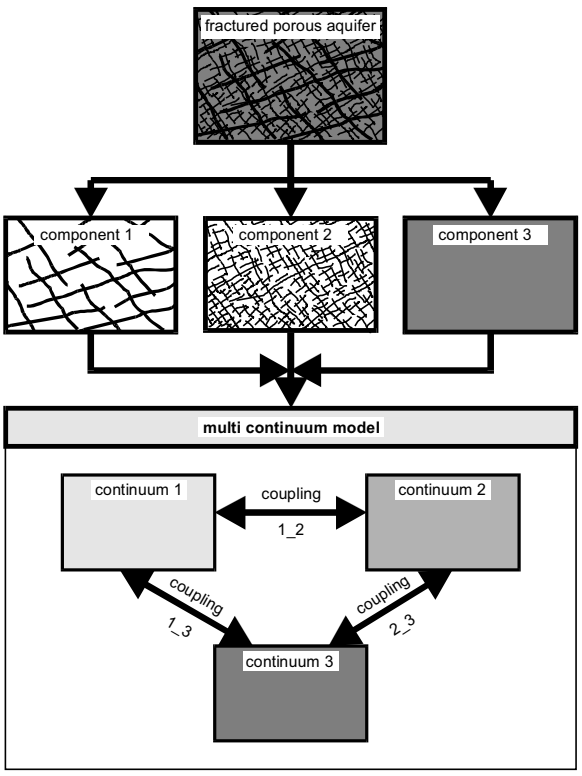

Figure 1. Solute exchange in fractured permeable formations (from Jansen 1999)

The objective of the proposed paper is to present the ongoing modeling using the multi-continuum approach and future development of investigations concerning flow and transport in fractured permeable formations within the Aquifer Analogue Project. The research of our project group during the third phase (2001 - 2003) of this project is focused on investigations concerning the possibilities and limitations of the multi-continuum model. Furthermore the sensitivity of coupling and transport parameters as well as the influence of the system conditions (saturated/unsaturated) on these parameters is going to be analyzed.

METHOD

The statistical evaluation (see e.g. fig.2) described in the proposed paper by Hase et al. (2003) is applied to laboratory and field data. The experimental results are analyzed by means of cluster analysis (Tuebingen project group). Based on this data a multi-continuum model is developed, which is capable of representing the characteristic properties of the fractured sandstone probe. Modeling results and measured breakthrough curves are compared and differences are discussed. The presented multivariate statistical approach can then be improved.

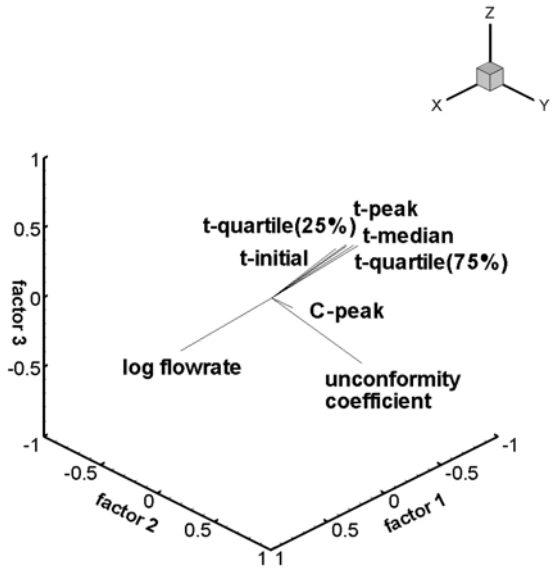

Figure 2. Factor analysis of parameters describing the shape of the breakthrough curves (from Hase *et al.* 2003)

REFERENCES

Hase M, Vogel T, Lagendijk VR, Köngeter J (2003) A statistical approach to build up a multi-continuum model describing flow and transport processes in fractured permeable sandstone, this issue

Jansen D (1999) Identifikation des Mehrkontinuum-Modells zur Simulation des Stofftransportes in multiporösen Festgesteinsaquiferen. Aachen: Eigenverlag (Technische Hochschule Aachen / Lehrstuhl und Institut für Wasserbau und Wasserwirtschaft: Mitteilungen; 118

The solution of the inverse problem of identification of fractional diffusion parameters

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A b s t r a c t : The fundamental solution of the classical equation of convection-diffusion is well-known and represents a symmetric Gaussian profile with exponentially decreasing "tails". However, there are laboratory (Benson 1998, Benson *et al.* 2001) and natural (Hatano and Hatano 1998, LeBlanc *et al.*1991) experiments indicating that in environments with internal structures (for example, with a fractal network of cracks) the dispersive carry submits to more complex laws. The same also concerns to strongly non-uniform environments. The dispersion of an impurity in these cases ceases to submit to the standard law $t^{1/2}$. Spatial profile of concentration may be asymmetrical and have so-called ”heavy tails” decreasing under the power law that can give cause for reconsidering of questions connected with radioactive waste burial. In this work the model of such non-standard carry and the methods of the inverse problem decision are given.

INTRODUCTION

The elementary linear model of the carry showing the specified properties is the model of fractional diffusion:

$$\frac{\partial C}{\partial t} = -v\frac{\partial C}{\partial x} + (1+\beta)\cdot\frac{D}{2}\cdot\frac{\partial^{\alpha} C}{\partial x^{\alpha}} + (1-\beta)\cdot\frac{D}{2}\cdot\frac{\partial^{\alpha} C}{\partial(-x)^{\alpha}}$$

where $\alpha \in [1;2]$ is the order of fractional diffusion, $\beta \in [-1;1]$ is the “skewness” or the factor of asymmetry, v denotes convective velocity, and D is the coefficient of diffusion.

The most interesting and practically important question is identification of fractional diffusion parameters by results of natural measurements. In this connection there are many approaches (Benson *et al.* 2001) though it is impossible to recognize any of them completely satisfactory.

STATEMENT OF THE INVERSE PROBLEM

In the elementary case the statement of the inverse problem for the equation of fractional diffusion is reduced to the following. It is considered, that two profiles of concentration $C_0(x)$ and $C_1(x)$ which are separated with the given interval of time T are known and it is required to find the parameters α, β and D. It is also supposed, that convective migration is absent. In this case the substitution $t^* = D\cdot t$ allows us to reduce quantity of unknown parameters down to two:

$$\frac{\partial C}{\partial t^*} = (1+\beta)\cdot\frac{1}{2}\cdot\frac{\partial^{\alpha} C}{\partial x^{\alpha}} + (1-\beta)\cdot\frac{1}{2}\cdot\frac{\partial^{\alpha} C}{\partial(-x)^{\alpha}}$$

It is necessary to note, that t^* is not time but the certain parameter describing a time interval between two profiles of concentration. As a measure describing distinction of two profiles of concentration at the various moments of time it is possible to use dimensionless variable:

$$\delta = \frac{\sum_{i,j}\left|C_{ij}^{0} - C_{ij}^{1}\right|}{\sum_{i,j} C_{ij}^{0}}$$

Thus the problem is reduced to following: two profiles of concentration $C_0(x)$ and $C_1(x)$ which are separated with the given time variable δ are known, and it is required to find the parameters of fractional diffusion α and β. If the real time separating these two given profiles is known, it is possible to find the coefficient of diffusion D.

SEARCH METHOD

One of the most reliable methods of the decision of the inverse problem is the search method: for various parameters $(a_i; b_j) = (1+i/N;-1+j*2/N)$, i, j=1,...,N, in regular intervals covering area interesting for us, the direct problem of fractional diffusion with initial condition $C_0(x)$ and the given time variable δ is solved and the result is compared to the real data. For the decision of the direct problem of fractional diffusion it is convenient to use a method of fast Fourier transformation (Goloviznin *et al.* 2002a, Goloviznin *et al.* 2002b). For each pair $(a_i; b_j)$ the mistake on norm *L2* between a profile received from the decision of the direct problem and a real profile is calculated $C_1(x)$. Pair $(a_i; b_j)$ that appropriate to the minimal mistake may be accepted for the decision of the inverse problem. For achievement of the greater accuracy the nearest vicinity of this approached decision may be covered with smaller grid and process of calculation on the described algorithm may be continued. Serious advantage of the search method in comparison with the other known methods is that it allows to find global minimum in the whole area of change of unknown parameters.

However, the search method is nonoptimal enough. For example, to define parameters of fractional diffusion with accuracy of 1 %, it is necessary to solve the equation of fractional diffusion about 10^4 times in the one-dimensional case, 10^8 times in the two-dimensional case and 10^{12} times in the three-dimensional case. Actually, such method can be used only for the decision of the one-dimensional problem.

NEURAL NETWORKS

For a choice of more effective methods of the decision of the inverse problem it is necessary to have some ideas about character of error function behaviour and possible presence on this function of local minima. With this purpose, the one-dimensional methodical problem in studying behaviour of error was solved for various parameters of fractional diffusion by the search method. The appropriate computer program was developed and a lot of calculations was executed which has shown, that local minima are absent and the unique global minimum has no ravine character. In the fig.1 the example of function of error for the one concrete pair (α, β) is given:

Presence of the unique minimum and absence of ravine behaviour allow us to use alternative, more economic methods of the decision of the inverse problem, basing on idea of gradient descent. One of the possible ways of realization of gradient descent is the algorithm of back propagation that widely used in the neural networks. From these reasons as the basic direction of

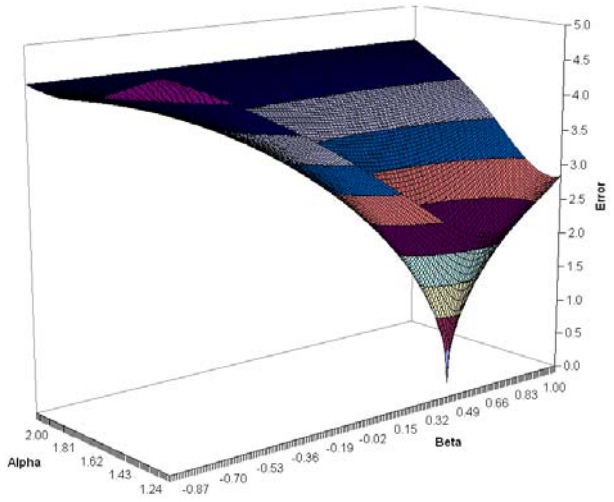

Figure 1.

the decision of the inverse problems of fractional diffusion both in one-dimensional and in multivariate cases, we chose the approach basing on construction, training and subsequent use of neural networks.

The basic idea of this approach consists in the following. In the beginning the direct problem of fractional diffusion with initial condition $C_0(x)$, the given time variable δ and various pairs parameters $(\alpha_i;\beta_j)=(1+i/N;-1+j*2/N)$, i, j=1,…,N is solved. Thus the settlement grid on spatial coordinate x undertakes enough detailed. So in the test one-dimensional problems it is considered 1024 cells. It is too large quantity in order to make them all as the inputs of the neural network, therefore initial settlement cells is necessary to replace by some aggregated cells, the values in which correspond summary concentration on united fine cells (in the one-dimensional case we used 16 aggregated cells).

Then, the data received by such way are used for training of the neural network. The vector from rather small number of the aggregated values of concentration is used as an input of the neural network, and the problem is that on rather small number of examples to train the neural network to distinguish with sufficient accuracy of the parameters α and β.

At the final stage the real data is used as an input of the network and the trained network should define values of the parameters of fractional diffusion adequate to them. For improvement of methodical questions the real data were emulated on the basis of numerical calculations by means of imposing on them various noise.

The methodical work that performed on the one-dimensional problem has shown that the success in use of neural networks essentially depends on their architecture. If in the output of the neural network both parameters was defined at once, even on the big set of training examples the parameter β would have a margin error about unit. Thus the parameter α as a matter of fact being the basic is defined precisely enough. It has resulted in the following methodical technique. The network with unique output value in the beginning would be under construction and its training on some set of various pairs (α, β) will be carried out. Then real data is used as an input of this network and there is a parameter α^*, then other network which output is one only value of parameter β is constructed, and its training on set of pairs (α^*, β) with the fixed value α^* will be carried out. If, after that, the real data is used as an input of the second network the parameter β is defined with a high degree of accuracy.

As a neural network the multilayered perceptron with two latent layers on 8 neurons in everyone was used. For realization of training of neural networks software package "Statistica Neural Networks" was used.

The analysis of accuracy dependence of fractional diffusion parameters definition from training examples quantity have shown that the accuracy of fractional diffusion parameters definition about 1 percent is reached using about 100 training examples. That is the offered method is approximately two orders faster than a search method.

Research of stability of the offered method in relation to noise in the input data is carried out. Noise of the following kind was considered:

$$C^{noisy} = C^{real} \cdot EXP(\sigma \cdot \xi)$$

where σ denotes amplitude of noise and $\xi \in [-0,5;0,5]$ is evenly distributed random variable. Calculations have shown that the method is effective for amplitudes of noise up to 20 percents.

The decision of the inverse problem by definition of fractional diffusion parameters by the offered method was generalized on the two-dimensional problem of fractional diffusion with the same diffusion constant in the both direction and without taking into account convective migration:

$$\frac{\partial C}{\partial t} = (1+\beta_x)\cdot\frac{1}{2}\cdot\frac{\partial^{\alpha_x} C}{\partial x^{\alpha_x}} + (1-\beta_x)\cdot\frac{1}{2}\cdot\frac{\partial^{\alpha_x} C}{\partial(-x)^{\alpha_x}}$$

$$+ (1+\beta_y)\cdot\frac{1}{2}\cdot\frac{\partial^{\alpha_y} C}{\partial y^{\alpha_y}} + (1-\beta_y)\cdot\frac{1}{2}\cdot\frac{\partial^{\alpha_y} C}{\partial(-y)^{\alpha_y}}$$

Estimations of quantity of the training examples necessary for a finding of parameters of this equation with accuracy in 5 percents are received. They show that using of neural networks for the decision of three-dimensional problems on computer based on Intel Pentium III 700Mhz processor it is required about 100 hours.

Now research connected with this subjects proceeds. The special attention is given to the decision of more general problem of fractional diffusion in view of convective migration and anisotropy of diffusion constant.

Besides the equations with fractional spatial derivatives the time-fractional diffusion equations and the combined equations with fractional derivatives both on time and on space are considered. Methods of the numerical solution of such equations in the one-dimensional case have already developed.

REFERENCES

Benson DA (1998) The Fractional Advection-Dispersion Equation: Development and Application. A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Hydrogeology

Benson DA, Schumer R , Meerschaert MM (2001) Fractional dispersion, Lévy motion, and the MADE tracer tests. Transp Por Media 42(1/2):211-240.

Goloviznin VM, Kiselev VP, Korotkin IA, Yurkov YI (2002) Some Features of Computing Algorithms for the Fractional Diffusion Equations (in Russian). Preprint IBRAE-2002-01, Moscow, NSI RAS.

Goloviznin VM, Kiselev VP, Korotkin IA (2002) Computational Methods for the One-Dimensional Fractional Diffusion Equations (in Russian). Preprint IBRAE-2002-10, Moscow, NSI RAS.

Goloviznin VM, Kiselev VP, Semenov VN, Korotkin IA, Yurkov YI (2002) The Decision of the Inverse Problem of Identification of the Fractional Diffusion Parameters (in Russian). Preprint IBRAE-2002-20, Moscow, NSI RAS

Hatano Y, Hatano N (1998) Dispersive transport of ions in column experiments: An explanation of long-tailed profiles. Water Resour Res 34 (5):1027-1033.

LeBlanc DR, Garabedian SP, Hess KM, Gehlar LW, Quardi RD , Stollenwerk KG, Wood WW (1991) Large-scale natural gradient tracer test in sand and gravel, Caape Cod, Massachusetts, 1, Experimental design and observed tracer movement. Water Resour Res 27(5):895 – 910

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